Dynamic physical analysis of long term economy-environment options.

by

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Abstract

This thesis presents a methodology for structural economy-enviornment simulation modelling (SEESM), and a demonstration of its application to New Zealand. The problem analysed in this thesis is the identification of long term *physical* limits on economic growth; in particular, a joint physical analysis of economic growth, technological development and resource scarcity.

It is important to analyse physical causes of technological change as this is an area the conventional economic growth models ignore. A growth model has been developed that includes physical influences on technological development while still recognising that investment accelerates the learning process. Although no clear conclusion can be made about the link between technological progress (learning) and energy analysis this is a promising area for further investigation.

The dynamic simulation modelling approach developed by Malcolm Slesser and others (ECCO) is reviewed, and a number of shortcomings identified. Three significant modifications are presented. First, growth in the new models is based on the neoclassical idea that technology is the main driver of economic growth rather than on classical growth theory which emphasis savings as the main determinant of growth. Secondly, the numeraire used in the models is a dimensionless index of volume so the model does not assume an energy theory of value. Finally, the model is based on a full set of input-output data which enables a more accurate analysis of flows between sectors in the economy. Thus, it has the advantage of the detailed structural information found from input-output analysis combined with the flexibility of simulation models. The resulting model is ideal for investigating the complex dynamic phenomenon of an evolving physical economy.

The purpose of this model is not to predict future economic growth but to highlight the physical assumptions required for any particular scenario. Once these physical assumptions have been identified, they are open to scrutiny and can easily be changed to test their importance.

A dynamic input-output model has been applied to the New Zealand economy and several different scenarios have been tested. The simulations include changing the overall growth rate of the economy, changing relative growth rates of different sectors, changing energy efficiencies, and introducing renewable energy technologies on a large scale. These simulations show that in some cases there are significant indirect physical flows that may not have otherwise been accounted for.

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Chapter 1: Introduction

A brief summary of the three Parts of this thesis is presented before more detailed introductions to the main ideas of each chapter are summarised. The first part of the thesis is a general introduction to the problems of sustainable development and a brief critique of some common methods of analysing the economy and environment. The conclusion of this review is that a physical model of the economy is necessary to understand sustainable development. The differences between ethical and physical constraints on economic growth are also briefly discussed.

Part two develops the theory and methodology of physical growth models. Economic growth theory is examined and found inadequate for understanding physical restrictions on economic growth. This theory does, however, identify the critical factors that determine the rate of physical economic growth; technological change, resource availability and pollution restrictions. Energy analysis, in various forms, is an alternative means of analysing the economy that has been used by many ecological economists. An investigation of energy analysis concludes that it is a useful tool for understanding the key factors that determine economic growth.

The third part of this thesis illustrates how the methodology developed in Part 2 can be applied to a real economy. Much of this section builds on Slesser's (1990, 1992) ECCO methodology and there is a detailed analysis of the methodology. The result of this analysis is that there are a number of ways where ECCO needs to be improved to correct for problems with the growth algorithm and the use of embodied energy as a numeraire. A simple global model is developed to illustrate how the methodology works before a more complex model of the New Zealand economy is developed. Although the New Zealand model is highly aggregated, there are a number of policy options that can be simulated which give insights about physical flows required to sustain an economy. From this, several areas that require further investigation have been identified.

1 Definition of the problem - the need for a physical model.

Chapter 2 briefly outlines the history of conventional and ecological economics. This history is important because of the long term nature of problems relating to sustainable development. The idea of physical restrictions on the economy is not new so valuable lessons can be learned from past attempts at the problem.

The purpose of Chapter 3 is to define sustainable development and related terms. Sustainable development is an extraordinarily broad term that can mean anything from sustainable economic growth to a steady-state economy. This thesis confines its investigation to the analysis of possible physical restrictions on economic growth although the role of ethics is discussed in Chapter 5. The pioneering work of Meadows et al. (1972) was the first large scale effort to understand the physical dynamics of economic development. There are, however, several problems with the Meadows approach that have caused it to be dismissed by many analysts (Cole et al. 1973, Tisdell, 1990). These problems are identified and solutions are developed in Part 2 of the thesis.

The most common approach to sustainable development is based on conventional economics and these methods are reviewed in Chapter 4. Any market failures are corrected (in theory) by using externalities and property rights. Cost benefit analysis can then be carried out to evaluate environmental problems. Cost benefit analysis is widely criticised for over simplifying complex ethical problems in an effort to put a price on everything. The conventional economic method of measuring resource scarcity is also discussed and compared to physical measures of resource scarcity. The conclusion of this chapter is that while economics attempts to include all aspects of the problem it fails to include the underlying physical interactions between the economy and the environment.

The important difference between ethical and physical restrictions on economic development is discussed in Chapter 5. The model developed in this thesis can only analyse physical restrictions on economic growth but many critical restrictions may be ethical. An example of this is the ethical problem of whether or not we should take the risk of enhancing the greenhouse effect by continuing to use fossil fuels. This type of decision is extraordinarily complex and justifies some discussion. Any decision like this requires some estimate of the future. The physical model developed in Part 2 will help resolve ethical dilemmas in that it clarifies the physical options that are available.

2 Developing the theory of a physical model

Chapter 6 explains Systems methodology and its relevance to sustainable development. Because of the complex nature of the sustainable development problem, the traditional reductionist scientific method is not suitable. Instead the systems methodology, which is concerned with the functioning of the whole rather than the individual parts, is more suitable. This new branch of science is rapidly becoming an accepted method of investigating complex problems.

The different types of physical flows between the economy and the environment are defined in Chapter 7 where the distinction is made between depletable, recyclable and renewable resources. The corresponding resource transformation systems within the economy that interface with the environment are the energy sector, the materials sector and the life support (agricultural and forestry) sector. The influence that polluting waste has on the economy is also emphasised. The quantity of polluting waste can be controlled to a certain extent by waste control systems. Monitoring the size of the resource transformation systems and waste control systems relative to the rest of the economy will give some indication of possible physical restrictions to economic growth.

Chapters 8 investigates the role of energy analysis in determining physical limits. The importance of energy in the running of a modern economy is emphasised along with the different forms of energy analysis. Although some authors have favoured an energy theory of value it is not widely accepted and not necessary for the analysis in this thesis. Energy analysis is a tool that is complementary to other forms of analysis and it is argued here that it is particularly useful for the analysis of long term physical economic limits. Three distinctly different forms of energy analysis have evolved - fossil energy analysis (Slesser 1990, 1992), solar energy analysis (Odum, 1971) and commercial energy analysis. Each of these different forms of energy analysis give different insights.

Chapter 9 analyses the dynamics of economic growth. Both the classical economic growth theory and the more recent growth theory of Solow can be represented by a systems dynamic model. It is argued that the production of an economy is better represented by a model like this rather than the simple production functions of conventional economics. Technological change and resource/pollution sink availability are singled out as the critical determinants of long term physical economic growth. In the past the rate of technological change has more than offset any diminishing returns due to pollution and resource scarcity. It is highly uncertain whether this trend will continue in the future. It is the assumptions about this trend that distinguish "doomsday" models from endless growth models. The following two chapters show how energy analysis can be used to understand trends in technology, resource scarcity and pollution. From this long term growth possibilities can be better understood.

Chapter 10 studies the links between technological change, economic growth and energy. The simple inclusion of a technology factor in the model developed in Chapter 9 is not sufficient for understanding how technology changes. The concept of a learning curve is introduced as it provides a quantifiable measure of the rate of change of technology. It has been found empirically that the cost of a good reduces in proportion to its cumulative production, i.e. we learn how to do things better and at less cost the more we do it. Each different goods or service has a different learning index that quantifies the rate at which learning takes place. It is difficult to know for sure if the learning rate will remain constant forever. It appears that goods that are more physically difficult to produce, i.e. require more energy, are more difficult to reduce the cost, i.e. have a lower learning index. This information allows some sort of quantifiable indication of future trends in technology. The other revealing information from the analysis of learning index of different goods and services is how they change over time. If the learning index increases then one would expect continued economic growth. If it is decreasing, however, economic growth may not be expected to continue at the same pace.

Including resource availability and pollution in a dynamic model are the subjects of Chapter 11. Resources that require more energy to make them accessible are more physically scarce. Numerous studies have verified the usefulness of energy as a measure of resource cost (Cleveland, 1984, Hall et al. 1992, Chapman and Roberts, 1983). This chapter builds on the work of these authors and shows how this theory can be applied to a dynamic economic model. The chapter also discusses how pollution can be included in a dynamic physical model. Once again energy is a useful indicator of the physical effort required by the waste control systems.

3 Application of physical models

Chapter 12 introduces the ECCO methodology developed by Slesser (1990, 1992). ECCO is perhaps the most advanced physical analysis that is designed to be applied to individual countries. It is a systems dynamic energy based model that include capital stocks and rates of capital formation and depletion. This allows dynamic problems such as the switch from fossil to solar energy to be investigated.

There are weaknesses with the ECCO methodology that are discussed in Chapter 13. These weaknesses relate to the assumptions about the causes of economic growth and the use of embodied energy as a numeraire. The discussion of economic growth theory in Chapter 9 is helpful for understanding how the ECCO series of models are set up to grow. The key factor that needs to be included in the ECCO growth algorithm is technological change. Several models are described that show the difficulties with using embodied energy as a numeraire. A method for solving this problem involving the use of a double set of accounts is also explained. The proposed changes significantly alter the results from ECCO models.

A model of the world economy is developed in Chapter 14 to illustrate the basic form of the model. It is easier to describe the methodology on a closed economy rather than the more complex economy developed in Chapters 15 and 16. Some comparisons are made with the ECCO models developed by Slesser and his colleagues to show how it is different. A number of different scenarios can be tested on this simple global model that give an idea of the versatility of this type of model.

A description of the New Zealand model is given in Chapter 15 along with the discussion of several new concepts such as input-output analysis and external flows in an open economy. Because the model is based on input-output data and it is methodologically different from ECCO it has been renamed SEESM (structural economy-environment simulation modelling) model. Several methods for checking the data and structure of the model have also been identified.

Several different scenarios have been simulated using the New Zealand SEESM model. These scenarios include changes in energy efficiency, changes in the overall and relative growth rates in the economy, a switch to renewable technologies and pollution restrictions. There several different indicators of sustainable development that are found from NZSEESM that give insight to long term physical limits. NZSEESM is designed to complement other forms of economic model and its relationship to these model is discussed.

The final chapter is a brief summary of the arguments of this thesis and the conclusions that can be drawn from them. The novel aspects of this analysis such as the physical growth theory, technology analysis and dynamic input-output energy analysis are highlighted.

Part 1: Definition of the problem - the need for a physical model

Chapter 2: History of economic-environment theory

The purpose of this chapter is to briefly describe the dominant economic ideas of the past 250 years to put the physical economic problem that is the focus of this thesis into perspective. It is necessary to understand how the ideas of modern economics have evolved, in order to understand how they may change in the future. The common methods of analysing environmental problems need to be discussed in detail in order to justify the method of approaching the problem outlined in this thesis. The first section is a brief history of mainstream economics. The second section is a history of the development of ecological economics.

1 Conventional economics

The process of producing a satisfactory mix of goods and services to meet the wants and needs of society is not an easy task. Before the advent of markets the two most common ways to cope with this complexity were tradition and command or a combination of the two. The command society has a ruling body that dictated what everyone should do. A society governed by tradition maintained stability by the enforcement of strict traditional rules. For example a blacksmith's son would have no option but to be a blacksmith. These were stable but economically stagnant societies. Heilbroner commented;

> The idea of "making a living" had not yet come into being. Economic life and social life were one and the same thing. Work was not yet a means to an end- the end being money and the things it buys. Work was an end in itself, encompassing, of course, money and commodities, but engaged in as a part of tradition, as a natural way of life (Heilbroner, 1980, p. 24).

Innovation was scorned and the status quo was defended as a way of protecting the "natural" order of things. These points are mentioned to emphasise that the idea of a growing economy or having more goods and services is a relatively new idea. At the same time one would not recommend a return to the past.

1.1 Adam Smith

In 1776 the moral philosopher Adam Smith wrote "Inquiry into the Nature and Causes of the Wealth of Nations" to explain how the market mechanism could organise society. This was a revolutionary idea, for the market system is not just a means of exchanging goods: "it is a mechanism for sustaining and maintaining an entire society" (Heilbroner, 1980, p. 25). Through the supply of labour and exchange of goods via money the most desired set of goods and services will in theory be produced at the least cost. Smith's theory stated that the economy could continually expand through the investment of part of the income to build more capital to produce more goods. Smith's philosophy was that one should not try to do good but let good emerge as a by product of selfishness. The message taken from Smith is that freeing the labour force and trade restriction would enable the economy to grow and for all to benefit.

1.2 Malthus and Ricardo

Malthus significantly undermined the optimism of Smith's doctrine. He wrote "An Essay on the Principle of Population as It Affects the Future Improvement of Society" in 1798. His argument focused on the problem of exponentially increasing population. His doctrine was that if population continued to increase there would not be enough land to grow crops to feed everyone. This emphasised the physical restrictions on the long term growth of the economy. He went as far as opposing aid to the poor as this would only draw out their inevitable death due to over population.

Ricardo was a successful stockbroker and a good friend of Malthus. He extended the simple idea of an absolute limit on land by noting that the quality of the land will get progressively worse as more land is required (law of diminishing returns). However, Ricardo was more concerned about the negative role of the landlord in the economy than the ultimate limits of agricultural production. Between the two of them they changed the overall mood of the times from optimism to pessimism. This led to the view of economics as the "dismal science."

1.3 John Stuart Mill

An important advance in economic theory was the distinction between distribution and allocation of resources and goods. Mill noted that there was nothing within the market mechanism that ensured the distribution of goods and services was "fair." The market mechanism only assured that resources were allocated where there were people willing to pay for them. Mill did not see a forever growing economy as a solution to poverty; he believed in more even distribution of economic goods and services. Many of the concepts of the steady state economy popularised by Daly (1980, 1991) can be related back to Mill (Perrings, 1987).

1.4 Victorian era

The mood of pessimism created by Malthus and Ricardo did not last long as there was rapid expansion of industrial economies through to the Victorian era. Heilbroner summed up the general economic views of the era by saying that:

> There is something about the technological orientation, the efficiency, the sheer dynamism of capitalist ways of production that makes the expansion of the system "irresistible" (Heilbroner, 1980, p. 200).

Changing technology and colonisation of new lands meant that the "expected" shortages of land and food did not eventuate. The industrial revolution was in full swing with seemingly no limits.

1.5 John Maynard Keynes

Keynes developed many of the economic theories that are still dominant today in his book "The general theory of employment, interest and money" (1935). He investigated some of the problems market economies can encounter. The great depression of the 1920s motivated his analysis of economic failure. Keynes noted that human perceptions of the economy played a dominant role in the performance of the economy.

> There are only perfectly virtuous citizens prudently attempting to save some of their incomes, and perfectly virtuous businessmen (sic) who are just as prudently making up their minds whether the business situation warrants taking the risk of buying a new machine or building a new plant. And yet, on the outcome of those two sensible decisions the fate of the economy hangs (in: Heilbroner, 1980 p. 264).

The Keynes philosophy justified a larger government involvement in controlling of the economy to overcome slumps in confidence[1]. He is responsible for the idea of government spending to "prime the pump" of the economy. This was a significant change for those who believed in the power of the market. It was noted by Heilbroner that: "Government spending never truly cured the economy- not because it was economically unsound, but because it was ideologically upsetting (ibid, p. 274). "

The economic problems of the seventies and eighties centred on inflation, large corporations and concerns about the environment and resources began to emerge. Focus on the environment and resources in mainstream economic has been increasingly important ever since then. Conventional economic methods of evaluating environmental problems are discussed in detail in Chapter 4.

2 Ecological economics

Ecological economics is a study of the interaction between the economy and the environment. Even though ecological economics has a rich history (Martinez-Alier 1987) it has not been very influential among mainstream economists. However, the ideas of ecological economics are gaining prominence (Costanza, 1989) as resource scarcity and pollution abatement become more significant problems. A brief history of the development of the ideas of ecological economics is presented along with a discussion on how this discipline relates to conventional economic theories.

2.1 Utility versus physical theories of value

Studies of economic scale have sometimes been called "Physical economics" as opposed to "conventional" or "utility" economics. Utility economics is concerned with efficiency and affluence, physical economics is concerned with security and sustainability. The time-horizons of the two are different. McRuer comments that: "Utility economics studies what people try to do. Physical economics studies only what they can do (McRuer, 1980)."

The common theme of debates on ecological economics is, how should economic output be measured? Should it be a subjective measure of value (utility) or a physical measurement of flow? It has been noted by Geddes:

> The distinction between theory of exchange and studies of the utilisation of resources is exactly the distinction between orthodox economics and the ecological-institutionalist economics (in: Martinez-Alier, 1987, p. 90).

In the 18th century the French Physiocrats made the first attempt to base economics in physical reality. Similarly, early ecological economists such as Geddes (1881), Podolinsky (1880), Sacher (1881) and Soddy (1926) proposed a more physical basis for economic value. These ecological economists acknowledged that human consumption could not be explained without introducing psychological and social considerations as well as the physical inputs. Patrick Geddes (in: Martinez-Alier, 1987) was typical of this group in that he took exception to the Walrasian idea that mathematical economists could do everything with no assistance from applied physics and biology. Conversely, conventional economists have difficulty with physical bases of value. For example, Walras did not want an invariable standard of value and repeated that:

> ... value depended on supply and demand (and that behind the function of demand, there was a function of utility for each consumer, whose value these consumers would wish to maximize) (ibid., p. 91).

The debate about subjective or physical measurements of economic output continued in the 1940s and 50s. The view held by most mainstream economists is summarised by Hayek:

> ... the scientific advance of economics depends on the consistent application of subjectivism, and that neither commodities, nor money, nor, food should be defined in physical terms, but rather in terms of the opinions held by people (1952, p. 31, in: ibid p. 149).

The biologist Hogben was sceptical of the economic methodology. His complaint against economists were twofold:

> Firstly, they proposed a theory of production without even a rudimentary knowledge of science and technology, which made them ridiculous: and secondly, they proposed a theory of consumption without a study of the origins of human needs (Hogben, 1936, p. 18-19 in: ibid, p. 152).

The idea of unlimited "needs" for economic output has been taken further by economists such as Galbraith (1958). He suggests that many of our "needs" are artificially induced by advertising.

2.2 An energy crisis?

Clausius (1885 in: ibid, 1987) is most famous for his formulation of the Second Law of Thermodynamics. He also recognised the important role energy has in the economy. It was Clausius who raised "the coal question". He noted that society is dependent on coal and that there is a limited supply. He saw the potential beginnings of a crisis. Jevons (1865, in ibid) also brought this potential problem to the public's attention (Perrings, 1987). These two are often quoted as examples of pessimists predicting a problem that did not eventuate. A significant part of this thesis is an analysis of why they were wrong, namely the role of technology in changing resource boundaries.

2.3 Carrying capacity

The concept of carrying capacity is useful for determining physical limits on human expansion. In 1902 Pfaundler[2] made an estimate of the carrying capacity for a population living on solar energy alone. He calculated that the earth would have a maximum carrying capacity of about five people per hectare if living from solar energy alone. Some regions of China have been sustaining 2/3 per hectare for hundreds of years so that it appears to be a reasonable estimate (ibid., p. 111). The concept of carrying capacity pioneered by Pfaundler has been used by many modern ecological economists (eg Slesser, 1987, Meadows et al. 1972, Rees et al, 1994) and this concept is expanded in the following chapter.

2.4 Perpetual motion of conventional economics

Frederick Soddy, a Nobel laureate in chemistry, is not generally recognised for his contribution to economics, although much of his later academic life was dedicated to this. He could not accept the perpetual motion assumption underlying macroeconomics. The perpetual motion idea is summed up by the following example.

> A man with, say, $20,000 invested at 5 per cent is in perpetual enjoyment without work of an income of $1,000 a year, and his heirs and successors after him. Consuming wealth every day of their lives, they always have the same amount as at first. This is not physics and it is not economics. Like all alleged examples of perpetual motion, it is a trick (in ibid, p. 131).

Similar arguments about the perpetual motion underlying modern economics have been noted by Daly et al. (1973), Peet (1992) and Gilliland (1977) (see Chapter 4). The problem with both these examples is that if all measurements are in dollars alone the concepts are no longer constrained by physical laws. It is a recurring point made by ecological economists that an economic analysis risks not making sense unless there is a corresponding physical analysis of the situation.

2.5 Reemergence of ecological economics

In the late sixties and early seventies the question of size of the economy arose again. Can an economy continue to expand for ever? Heilbroner summarises economists views on this question:

> Economic opinion divides sharply on this issue. Some economists, perhaps a majority of them, do not believe that a continuation of safe growth will be a problem in our time. In part, such optimistic observers pin their faith on a continuation of our long record of finding technological escapes from close corners (Heilbroner, 1980, p. 305).

This is perhaps an understandable argument, as the historical evidence of technological innovation solving our short term material problems is vast (Barnett and Morse, 1963). However, the analysis of technological innovation needs some physical justification (see Chapter 10). The following chapter takes up from here by trying to define the problems of sustainable development and how they can be understood.

Notes

1. Market confidence is still a key economic indicator.

2. Pfaundler also recognised the importance of energy rather than materials (in: Martinez-Alier, 1987, p. 106)

Chapter 3: Sustainable Development - A discussion of concepts

The aim of this chapter is to introduce some concepts of sustainable development along with a number of definitions. The major argument behind the "limits to growth debate" and the concept of carrying capacity are discussed. This leads on to a discussion of some approaches and indicators of sustainable development.

1 What is the problem?

The essential problem of sustainable development is that all economic activity is totally interlocked with the Earth's ecology, through physical flows, but we do not fully understand many ecological processes and the long term effects of our actions on the biosphere (Ehrlich, 1994). It is not known whether the activities of modern humans are compatible with the continued functioning of the biosphere. Underwood and King describe the problem:

> The flow of energy-matter obtained from natural resources interacts with the biosphere to create environmental problems. This interaction is determined by the immutable laws of thermodynamics and conservation. Social institutions must conform to this reality: reality will not conform to the institutions. Herein lies the heart of the sustainability issue (1989, p. 323).

The list of institutions and authors that have recognised the problem in some form or another is long and varied. The reason the problem has come to the fore recently is that the combined effect of the world's human population is now large enough to significantly affect the biosphere. In the past this was not the case. The common method of overcoming local physical limits in the past was to colonise new areas of land and this often resulted the discovery of land of better or equal quality that was easy to colonise. However, current colonisation options, such as space and the ocean, appear to be too costly for mass migration.

1.1 Defining sustainable development

It is possible to get lost in the literature on defining sustainable development. Pearce et al. (1989) have found over twenty different definitions ranging from sustaining the environment to sustaining economic growth. Barbier (1987) suggests that "It may be extremely difficult, if not impossible, to define sustainability in any analytically rigorous way" (Barbier. In: Tisdell 1990, p. 26). Similarly Solow (1993) suggests sustainable development is not meaningless, it is just inevitability vague. This ambiguity and vagueness may be a positive thing because it ensures that the paradigmatic differences surrounding the concept are not lost. These paradigmatic differences and how they affect ethical decisions relating to sustainable development are discussed in Chapter 5.

Due to the complexity and breadth of the concept of sustainability it is not possible to investigate all angles. It is primarily the physical questions of technological change and resource availability that are the subject of this thesis. The aim of this chapter is to briefly outline the problem of sustainable development, in order to clarify the issues to be investigated in this thesis. Several methods of analysing sustainable development are also discussed, along with their merits and shortcomings.

Daly suggests sustainability is like justice: it is difficult to say what it is just but easier to say what it unjust. Similarly it is difficult to define sustainability but it is entirely possible to say what is unsustainable. That gives a starting point for analysing sustainability. From this, some biophysical indicators of sustainability can be found in quantitative terms.

A significant proportion of work relating to sustainable development has gone into defining and calculating biogeophysical factors that measure sustainability. A good summary of these indicators of sustainability is given in Munasinghe and Shearer (1995, p. xxxiii). These indicators include things such as soil acidity, erosion, genetic reserves, etc. The models developed in this thesis aim to simulate how the physical flows in the economy would react to externally given physical restrictions such as land use limitations. This thesis focuses on economic and technological physical problems rather than ecology based physical problems.

1.2 Weak and strong sustainability

An important distinction between weak and strong sustainability has been made in the literature (Daly, 1991, Pearce, 1990). Both definitions state that the total amount of capital should be constant or increasing so a constant or increasing income can be sustained. The difference is in the type of capital that is to be sustained. The two different types of capital are *natural* capital and *human-made* capital. Natural capital includes all plants, animals, habitats and ecosystems. Human-made capital includes all machines, buildings and infrastructure that have been built by humans. With weak sustainability it is the total natural and human-made capital that must be sustained. This definition assumes that a loss in natural capital can be compensated by increasing human-made capital through investment and technology (Solow, 1993). Strong sustainability states that natural capital must be maintained. The essential difference between the two definitions is that weak sustainability assumes that human-made capital can replace natural capital, whereas strong sustainability assumes natural capital is irreplaceable and that natural capital and human-made capital are complements not substitutes (Daly, 1991, Perrings, 1987).

The concept of sustaining capital to maintain income is generally accepted. It has been noted by Solow (1993) that all economists are sold on this idea. The contention is whether human-made capital can replace natural capital. The aim of this thesis is to investigate the dynamics of increasing human-made capital to see if there are any limits on it imposed by physical laws. If it is found that there are limits of human-made capital then this will inevitably show there are limits on the total physical capital[1].

1.3 Interdisciplinary nature of the problem

The question of sustainability needs a multidisciplinary approach due to the many areas of science that it covers (Costanza, 1991, Daly, 1991). It is important to split the question of sustainability so that the different parts of the problem are not confused.

This can be illustrated by the example of conserving rain forests. There is an ethical question about the quantity of species extinction that is morally acceptable. The physical question relates to the functioning of rain forests within the biosphere. It should be the job of the ecologist to determine the risks involved in destroying the rain forest and then the public can decide what risks they are prepared to take. It is important that the public is not asked to judge what the risks are if they have no expertise in this area[2]. Similarly, geologists should be consulted about resource depletion and atmospheric scientists should be consulted about the enhanced green house effect and the ozone hole. Physical scientists estimate the risks involved and the public then acts on this. The importance of recognising the difference between physical and ethical questions is further discussed in Chapter 5.

The physical question to be analysed in this thesis focuses on the role of technology in changing resources availability and carrying capacity (i.e. increasing human-made capital). As explained in later chapters assumptions about technology are one of the key differences between optimists and pessimists in the growth debate. There are, however, some physical laws that can be applied to understand how technology may change in the future.

2 The growth debate

As briefly outlined in Chapter 2 the "growth debate" has a long history. This section outlines some major differences between those who see economic growth as a solution to environmental problems and those who see it as the cause of the problems.

The expectation of economic growth is universal in modern economies. Daly has noted that:

> ...economic growth is the most universally accepted goal in the world. Capitalists, communists, fascists, and socialists all want economic growth and strive to maximise it (1991, p. 8).

Is economic growth good or bad for the environment? Some argue that it is good for the environment in that it allows people to have extra resources that can be used to clean up and protect the environment. This view is summed up by the International Chamber of Commerce:

> Economic growth provides the conditions in which in which protection of the environment can best be achieved, and environmental protection, in balance with other human goals, is necessary to achieve growth that is sustainable (ICC in: Ekins, 1992, p. 275).

Some authors even view environmental degradation as a benefit for the economy. Bostian says that:

> ..the planet has become so messed up that pollution control and cleanup has the potential to be a gargantuan business. Right now, something like $130 billion is being spent worldwide on pollution control and cleanup, but that may be well above $1 trillion by the turn of the century. That's good for the economy in terms of creating jobs... (Bostian, 1992, p. 14)

This type of view has been developed in Inglehart's post-materialist thesis in environmental sociology (Inglehart in: Martinez Alier, 1994). Inglehart's thesis basically says that as material goods become more abundant, they become less valuable (decreasing marginal utility) relative to environmental goods and services. Aesthetic and intellectual satisfaction become more important. People care about the environment more in rich countries, as they have the time to do so. Countries that are not so well off cannot afford the "luxury" of a clean environment. They are "too poor to be green" (Martinez-Alier, 1994).

However, this post-materialist view ignores the negative feedback that increasing growth has on the environment. An alternative view is that as an economy grows it requires more resources and puts more pollution into the environment. Tinbergen and Hueting think that: "Environmental degradation is a consequence of production and growth (1992, p. 3)." Similarly Perrings (1987) considers that the relief of the environmental constraints to growth is not simply a matter of throwing more resources at the problem. Martinez-Alier suspects "that growth increases environmental costs faster than benefits from productivity thereby making us poorer, not richer (1994, p. 1029)". This link between the resource and pollution flows and material well being is at the heart of the sustainability problem.

2.1 Definitions of growth

Much of the discussion surrounding the limits of growth debate surrounds the definition of growth. Ekins and Jacobs (1994) make the distinction between three different types of growth: growth in the economy's biophysical throughput; growth in production (or income) as measured by GDP; and growth in human welfare. The link examined in this thesis is that between biophysical throughput and GDP[3].

Another important definition is the difference between growth and development. The difference between growth and development in an economy is best explained by analogy. Growth occurs early on in the life of animals. Once maturity is reached physical growth stops but development continues (Daly, 1991). Zero growth does not imply a static situation. Odum also notices the difference:

> Young ecosystems seem to emphasize production, growth and quantity, whereas mature ecosystems emphasize protection, stability and quality (Odum, 1969, in: Daly, 1991, p.103).

3 Carrying capacity

The concept of carrying capacity[4] has been used to conceptualise physical limits to growth of the human species. Biologists and ecologists note that in a given niche the population will increase exponentially until it reaches its carrying capacity[5]. This limit to growth is one of the few universal laws of Biology (MacKenzie, 1994) but humankind has an advantage over other species when it comes to carrying capacities. This view was best put by sociologist Catton:

> Man is like every other species in being able to reproduce beyond the carrying capacity of any finite habitat. Man is like no other species in that he is capable

of thinking about this fact and discovering its consequences (Catton, 1980, p. 6).

It may also be debated that human kind has the ability to alter the carrying capacity. By how much and for how long is the key question of sustainability.

The graphs in Figure 3-1 sum up different possible options for the future[6]. The first graph shows that as the population increases the carrying capacity increases due to technological developments. This is the continuous growth scenario proposed by many economists. The next graph is the best possible scenario if there is some form of absolute physical limit; exponential growth tapers off to a sustainable level compatible with the limits (sigmoidal growth). The worst case scenario is shown in by the third graph; overshoot is so great that it causes a collapse in the ecosystem to such an extent that the carrying capacity is permanently reduced. In the last graph the carrying capacity increases but it does not increase for ever as in the first graph. This graph shows the population has exceeded a carrying capacity of a primitive technology society. However, the carrying capacity has increased with increased technological knowledge. If the rate of increase of the carrying capacity is less than the rate of population increase then there will be pressure on the material standard of living. This shows that there are potential limits on material wealth even if the carrying capacity continues to grow. Another possibility that is not illustrated is that there could be a small overshoot of the carrying capacity. The population and economy will partially collapse as a result and then oscillate about the carrying capacity. The aim of this thesis is to estimate which scenario is the most realistic and how close we may be to any limits.

This dynamic concept of carrying capacity is consistent with recent theories of co-evolution. That is, the population does not adapt to a niche but the population and the niche co-evolve together. Some recent authors have tried to do detailed calculations of local carrying capacities (Rees and Wackernagel, 1994). Although these "footprint" calculations give a reasonable measure of carrying capacity, they are a static analysis which ignores the possibility of changing technology. As outlined in following chapters this is a severe limitation of the methodology.

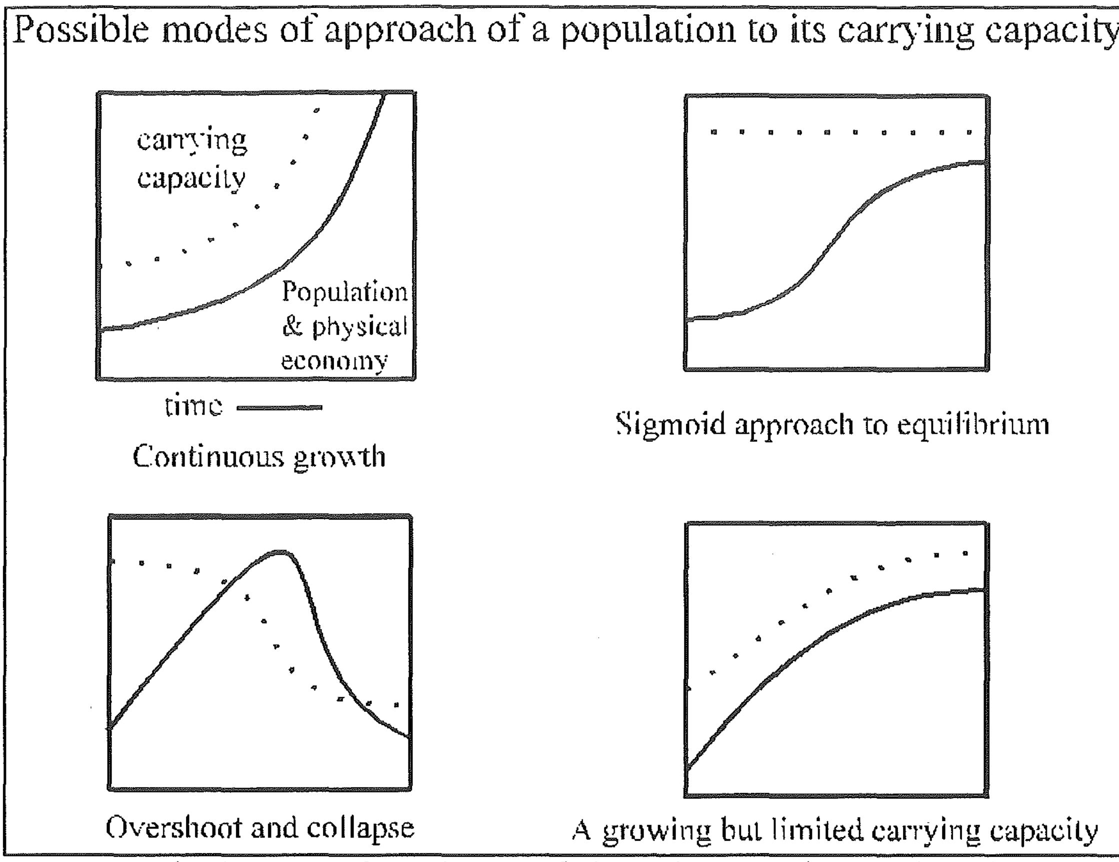

Figure 3-1 The dynamics of population and physical economy approaching the carrying capacity. Which mode of behaviour best describes economic growth?

4 Approaches to sustainable development

Given the complexity of a question such as sustainability, how should one analyse the problem? Norgaard (1989) came to the conclusion that sustainability is too important, too multidimensional, and too poorly understood for societies to rely on one methodology. Though no one methodology can be logically correct, the use of multiple methodologies will reduce the likelihood of making a significant error.

The modelling methodology developed in this thesis is a dynamic input-output physical analysis. It is by no means the definitive methodology but hopefully another tool to try to understand the problem of sustainable development.

The steady state economy of Daly (1973, 1980, 1991) and the limits to growth models of Meadows et al. (1973) are briefly described as they have made significant contributions towards sustainable development methodology. Perhaps the most common method of analysing sustainable development is conventional economics. The following chapter contains a very brief discussion and critique of economic methods.

4.1 The steady state economy - Separate questions of allocation, distribution and scale

Daly has popularised the idea of splitting questions of sustainable development into three separate questions: What is the ultimate size of the economy? How should the products of the economy be allocated? How should these products be distributed (Daly, 1991)[7]? The question of what size the ultimate size of the economy should be is new to conventional economists. Physical and ethical limits need to be determined to decide what size of the economy should be. From this, standard economic methods can be used to allocate and distribute the goods and services of the economy. The methodology described in this thesis is designed to give insights on issues of size only.

Splitting questions of sustainable development into three separate questions is the basis of the "steady state economy." Daly (1973) and Boulding (1966) have developed and expanded the ideas of a steady state economy first proposed by John Stuart Mill[8]. The choice of the name "steady state" may imply a static economy to some but Daly's writing on the topic certainly does not imply a static state. Perhaps a more appropriate name may be "an ethically and physically bounded economy." The range of physical flows between the economy and the environment is bounded by the ethics of the population and the physical restrictions. The nature of economic activity can continually develop within these boundaries to meet the needs of the population. The boundaries are not necessarily static either; they can change as information becomes clear or societies' values change. Boulding succinctly states that:

> The concept of sustainability does not refer to some equilibrium state, not even the stationary state of classical economists, but to a sustainable evolutionary process of continuous change... We certainly don't want the existing world structure to be sustainable. We want to improve it (Boulding, quoted in: Allen and Peet, 1994)

> the stationary state of classical economists, but to a sustainable evolutionary process of continuous change... We certainly don't want the existing world structure to be sustainable. We want to improve it (Boulding, quoted in: Allen and Peet, 1994)

The discussion on the steady state by Daly implies that the throughput of materials should be minimised. This is not necessarily valid. It has been pointed out by O'Connor (1994) it is not necessarily the quantitative flow that needs to be reduced but the qualitative changes in the flow of throughput. However, the important point is that the outputs are bounded by physical and ethical restrictions.

4.2 Limits to growth modelling

The Club of Rome popularised the word "problématique" to describe the complex problems facing the world. They commissioned a study by Meadows et al. (1973) titled "The Limits to Growth." This dynamic simulation model based on the work of Forrester (1971) brought the potential limits of economic growth to the public's attention. The model was the first significant attempt to model the physical flows of the economy and their interactions with the environment. The work in this thesis, in a number of respects, is an extension of the methodology developed in the Limits to Growth project. A comparison of the models developed in this thesis and the Limits to Growth models is given in Chapter 12 and 16.

5 Indicators of sustainable development

As discussed above it is difficult to define sustainability but much easier to define unsustainability. Most indicators of sustainability are usually indicators of unsustainability. For example the quantity of depletable resources used in the economy gives an indication of the unsustainability of the economy. If this rises it indicates that the economy is becoming more unsustainable and therefore less sustainable.

Other indicators of sustainable development include Slesser's (1992) Renewable Energy index and Vitousek, et al. (1986) net primary production (NPP). A necessary condition for a sustainable society is that it has a sustainable energy supply. The Renewable Energy Index (REI) is the proportion of energy supplied to the economy from renewable energy sources. The net primary production is a measure of the total quantity of the earth's solar resources that are used directly and indirectly to support the human species. Vitousek, et al. estimate that 25% of potential global (terrestrial and aquatic) NPP in now appropriated by human beings. If only terrestrial NPP is considered, the fraction rises to 40%. This indicates that there is not much room for increasing the amount of solar radiation available to humans. Other indicators of sustainable development are discussed in Chapters 9, 14 and 16.

6 Scope of this investigation

Some issues surrounding sustainable development have been outlined and the question to be analysed in this thesis has been narrowed down to: "what are the possible physical limits on the long term expansion of human-made capital?" There are many complex ethical, legal, political and social questions that need to be answered to operationalise the concept of sustainability. For simplicity, these complicated issues are put to one side and only the physically possible options investigated. There are still many people who believe that there are no real physical limits on economic growth (Simon, 1981). The models developed in this thesis aim to clarify possible limits, because the answer to this question of physical limits will radically affect the policy decisions we make today (Barnett and Morse, 1963).

Notes

1. The total quantity of natural capital is limited by the size of the planet.

2. It may well be that it is the locals who understand the ecology of an area better than ecologists. The point being made is that the physical and ethical questions are quite different.

3. The link between GNP and human welfare is briefly discussed in Chapter 4.

4. Ecologists define "carrying capacity" as the population of a given species that can be supported indefinitely in a defined habitat without permanently damaging the ecosystem upon which it is dependent (Rees and Wackernagel, 1994, p. 369)

5. There may be some overshoot and collapse of carrying capacity or an oscillation around the carrying capacity.

6. Adapted from Meadows et al. (1992 p. 108). The original diagram included an oscillation and over shoot but did not include the increasing carrying capacity levelling off.

7. Although the questions are separated they are not independent (Prakash and Gupta, 1994). It will always be a iterative process to find an acceptable size, allocation and distribution. Daly stresses that there are different *policies or methods* required for each of the three different questions

8. Mill actually called it a stationary state economy.

Chapter 4: Conventional economic approaches to sustainable development

The previous chapter outlined some of the key issues of sustainable development. The next sections outline the conventional economic approach to sustainable development. Traditionally, the key question the economists ask are; What variety of goods should be produced and in what quantities? How should these goods be produced? How should the goods produced be distributed? Ecological economists argue that there is another important question to add to this list: How big should the economy get? Conventional economists believe that this last question can be answered by extending the economic rationale to the environment and resources. The methods and rationale behind these economic techniques are introduced. A substantial discussion of conventional economic methods is beyond the scope of this thesis so the discussion in this chapter is limited to how economic theories relate to the physical model developed later in the thesis. The conclusion is that conventional economic methods are not sufficient to understand the underlying physical processes required to maintain economic growth.

1 Economic approaches to environmental problems

1.1 The market mechanism

If resources are distributed reasonably fairly and people have roughly equal opportunities to participate in a market, then the market mechanism may be the most democratic way of allocating resources yet invented. However, it has been stressed by Daly that the allocation of resources is only one part of the broader economic question.

> The market, of course, functions only within the economic subsystem, where it does only one thing: it solves the allocation problem by providing the necessary information and incentive. It does that one thing very well. What it does not do is solve the problem of optimal scale and of optimal distribution. The market's

> inability to solve the problem of just distribution is widely recognised, but its similar inability to solve the problem of optimal or even sustainable scale is not as widely appreciated (Daly, 1991, p. 35).

Many authors argue that markets are the most economically efficient way off achieving a given pollution goal - ie at least cost (Read, 1994, Blinder, 1987). The key question is, do markets offer any useful information on what the level of pollution or rate of resource use should be?

1.2 Externalities. Cost benefit analysis.

Market failure occurs when an imperfection in a price system prevents an efficient allocation of resources (Samuelson and Nordhaus, 1989). These failures occur when an activity, such as polluting, affects others who are not compensated for the inconvenience. Economists try to fix this by putting a price on the externality so that the cost is included by the people causing the problem. Once a value has been determined, the costs and benefits can then be estimated so a project's worth can be evaluated. The cost of a specific response for fixing an environmental problem is usually easy to calculate[1]. The benefits are usually much harder to calculate, as they involve ethical and complex physical questions. Economists have built up a number of methods for putting a dollar price on these externalities, and cost-benefit analysis is now a major subdiscipline in economics.

The conventional method of measuring environmental externalities is by surveying peoples' willingness to pay. The flaws of this approach have been highlighted by Schulze:

> This approach (in which only members of the present generation are consulted) assumes that individuals are well informed and are the best judges of their own welfare, such an approach is contrary to the way that societies routinely choose to make decisions regarding the suitability of the environment. Who would advocate using survey results as a means of choosing acceptable exposure levels for lead, radioactive material, or coliform bacteria (Schulze, 1994, p. 198)?

This example illustrates how confusing problems can get if the physical and ethical components of the question are not separated (see Chapter 3 and 5).

Pearce (1975) notes that economists are in a no win situation in that if they include costs they are criticised for "valuing the invaluable" but if they do not they are ignoring intangibles. Booth (1994) suggests that complex ethical problems are just too complicated to be the subject of monetary analysis: "Moral decisions are never as easy as calculating benefit-cost ratios (Booth, 1994, p. 251)" If cost benefit analysis is applied then the assumptions and omissions are so large that the whole process is questionable. Schulze's (1994) analysis of cost benefit analysis concludes that:

> In essence, when cost-benefit analyses are applied to broad policy questions, their compelling feature - reduction of complexity - is largely illusory (Schulze, 1994, p. 199).

1.3 Property rights

Property rights are an essential feature of the market mechanism that provide incentive for utility maximising individuals to look after their property. If the resource is privately owned then there is incentive to look after it. If there is no owner of a resource and no rules governing its use then it will tend to be over used. This situation is discussed in detail by Hardin (1968) in his famous paper "The Tragedy of the Commons." This paper is often associated with the idea of privatising commonly owned assets as a method of protecting resources, when Harden actually prefers the regulation of commonly owned property. As pointed out by Aguilera-Klink (1994) it is not common property that is the problem but free access to common property that is the problem. If access to a resource is regulated then the tragedy will not necessarily occur. A significant section of Hardin's influential paper is dedicated to this point. Hardin develops the idea of mutual coercion to set the rules that ensure sustainable management.

Examples of common property are the sea and sky. Each of these is subject of abuse as there is often no direct incentive for individuals or firms to protect the resource. It has been argued that if the resource is divided and privately owned then the resource will be protected. There are obvious logistical problems with this idea but more importantly it ignores the overall systems functioning of the resource. Privatising all commonly owned resources is still seen as "the solution" to all environmental problems by some (eg DiLorenzo, 1993).

1.4 Discount rate

One of the major difficulties with economics is deciding how future generations should be accounted for. The discount rate is a reflection of how valuable future consumption is seen to be[2]. There is a significant section of the literature devoted to analysing what the future discount rate should be. However, selecting a discount rate depends on your perception of the future. Georgescu-Roegen notes that choosing a discount rate is not really an economic question; it is an extra-economic question (Georgescu-Roegen, In: Martinez-Alier, 1987, p. 168). The "choice" of discount rate depends on assumptions about the substitutability of resources and capital and technological progress. Simon (1981) explains the logic of having a high future discount rate:

> Because we can expect future generations to be richer than we are, no matter what we do about resources, asking us to refrain from using resources now so that future generations can have them later is like asking the poor to make gifts to the rich (Simon, 1981, p. 151).

Analysts that do not share Simon's optimistic future will, correspondingly opt for a lower discount rate. The aim of this thesis is not to determine the future discount rate but to clarify some physical restriction on future options so that we may better understand what likely futures might be.

1.5 Neoclassical economic theory

Neoclassical economic theory has been popular for analysing resource and environmental problems rather than the limits to growth type model of Meadows et al. (1972). The reasons for this are illustrated by Feige and Blau (1980, p. 110)

> It is our view that the application of neoclassical economic theory to the natural resource area provides a much more powerful and illuminating framework for considering these issues and allows consideration of factors that will be powerful determinants of future resource use but which have been consistently underestimated by the forecasts of doom through out the years. The most significant of these factors are surely the extraordinary substitution possibilities (in both consumption and production) induced by changes in the relative prices of resources and the often unpredictable and dramatic technological innovations which provide alternative means of satisfying human needs (Feige and Blau, 1980, p. 110).

Substitution and technological change are key issues in the growth debate. It is, however, questionable to extrapolate these technological trends without a knowledge of the physical transformations these trends assume. Feige and Blau tend to make the assumption that technological innovation will solve any problems without backing it up with a physical analysis. It has been noted by Perrings (1987) that something as woolly as the belief that "we will think of something" is a key assumption in models of modern resource economists.

1.6 Price as a measure of scarcity

Barnett and Morse's (1963) book "Scarcity and Growth" is the seminal economic analysis of the role of resource scarcity in the economy. They tested two hypotheses to see if resources are becoming more or less scarce. The first hypothesis is that if resources are scarce their real price should be increasing; the second, weaker hypothesis is that they would expect the extractive sectors to be more expensive relative to other goods in the economy (ibid, p. 8). Their analysis showed that natural resources have been steadily reducing in price relative to labour and are in fact becoming less "scarce."[3] Their proposed mechanism for this increasing availability of resources is:

> ..the increasing scarcity of particular resources fosters discovery or development of alternative resources, not only equal in economic quality but often superior to those replaced. Few components of the earth's crust, including farm land, are so specific as to defy economic replacement, or so resistant to technological advance as to be incapable of eventually yielding extractive products at constant or declining cost. (ibid, p. 10).

Barnett and Morse consider the technological advance to be inevitable:

> Not only ingenuity but, increasingly, understanding: not luck but systematic investigation, are turning the tables on nature, making her subservient to man (ibid, p. 10).

This work has been influential among economists as it clearly showed that resources were becoming more available relative to human labour. Other economists such as Simon (1981) went further to say that:

> ...natural resources are not finite in an economic sense... resources will progressively become less scarce,.... and will constitute a smaller proportion of our expenses (Simon, 1981, p. 88).

Some evidence from Hall et al. (1986) suggests that this is not true for the USA. Resources as a percentage of GNP have risen from 4 to 8% from 1973 to 1985 after remaining constant for the previous 70 years[4].

Many economists are critical of physical measures of scarcity such as those proposed by Meadows et al. (Cole et al. 1973, Tisdell 1990). The models of Meadows et al. suggest that we are running out of resources and we should stop using them at the rates we are. This conservation argument is not accepted by mainstream economists:

> Sustainability of natural resource use, even renewable resource use, is not a worthwhile goal in itself and, indeed, may reduce human welfare rather than add to it (Tisdell, 1990, p. 28).

The method used by Meadows et al. to determine resource scarcity is to measure the total quantity of resources available and analyse the rate of resource use. From this an estimate of when we might run out can be found. A major criticism of this is that it is often not economic to know exactly how many resources there are. When there is a perceived scarcity people will look for more but they are not likely to look until it is worth their while. The number of years' worth of "proven resources" has remained relatively constant for much of the century for most of the major resources. The main criticism from economists is that Meadows et al. take no account of how the price mechanism can induce research and technical change that may over come a resource or pollution problem.

There have been several detailed criticisms of the Barnett and Morse work (Chapman and Roberts, 1983, Hall et al. 1986, Norgaard, 1990). The main problem with their analysis is that they assume that technical progress will continue to out pace any resource scarcities. There are also problems with the method of calculating real prices and of the process of taking data from an open economy and assuming it is valid for the world (see Chapman and Roberts, 1983, p. 5-7).

Norgaard (1990) highlights the circular nature of using price as a measure of resource scarcity. The economic theory for using price as a measure of scarcity can be reduced to the following simple syllogism: (Norgaard, 1990)

> Major premise: If resources are scarce, and
> Minor premise: If resource allocators are informed of resource scarcity,
> Conclusion: Then economic indicators will reflect this scarcity.

So allocators need to know how scarce resources are in order for the prices to reflect this scarcity. Norgaard expresses this simply:

> .. if the conditions necessary for the economic analysis of scarcity existed, there would be much less reason to undertake economic analysis of scarcity (ibid).

Norgaard poses the embarrassing question: why undertake economic analyses of scarcity if resource allocators are informed of scarcity? We could simply ask the allocators about scarcity[5]. However, the aim of the economic analysis is essentially to put a numerical easily understood figure (price) on the resource scarcity that will reflect how people use it. Alternative measures of scarcity are outlined in Chapter 8.

Perhaps the biggest error of the Barnett and Morse study is that they assume technological "progress" can continue for ever and that we will always be able to outsmart Mother Nature. Although their evidence strongly suggests this is true for the period covered by the survey, this does not prove that the trend will continue ad infinitum. It does not make sense to extrapolate trends without physical understanding of the trend.

1.7 Substitutability

A model that assumes infinite substitutability is as useful as a model that assumes no substitutability. Either of those beginning assumptions determines the outcome of an economic growth model. A model needs to be able to test the significance of hypothesised limits to substitution. The importance of substitutability is emphasised by Solow:

> If it is very easy to substitute other factors for natural resources, then there is in principle no "problem." The world can, in effect, get along without natural resources, so exhaustion is just an event, not a catastrophe[6] (Solow, 1974, p. 11).

The optimistic view on substitutability is that "reproducible capital is a near perfect substitute for land and other exhaustible resources. (Nordhaus and Tobin, 1973, p. 204). Physical scientists tend to be a little more sceptical as to the ultimate resource substitutability. Chapman and Roberts think that:

> Although there is some substitution possible, enough to absorb shortages of a few resources, it is obvious that capital cannot function without substantial inputs of natural resources (Chapman and Roberts, 1983, p. 10).

It is interesting to note how some economists' views on substitution change to suit the policy they are supporting. For example, 17 years after Nordhaus's (1973) optimistic paper on substitution he says that: "There are simply no substitutes for many of today's uses of fossil fuels (1990, p. 20)." Here Nordhaus is arguing for reasons not to restrict carbon dioxide emission. He thinks this would be too costly. This shift in thinking by some economists on substitution has also been noted by Read:

> ... the profession jumped in to proclaim the adaptability of the economic system, the implausibility that any input is technically essential, the opportunities for

> substituting alternatives for oil and the existence of "backstop" technologies which would always be available to come to the rescue if the growth process began to get stuck. With global warming, however, the profession has been proclaiming the difficulty in adapting to a non-carbon future, the near-essentiality of fossil fuels, the absence of backstop technologies, and the great cost of responding to global warming in terms of a slowing of the growth process (Read, 1994, p. 23).

These backstop technologies are supposed to provide a ceiling for the market price of the natural resource. Nordhaus used breeder reactors as a backstop for his resource scarcity model in 1974. His "conservative" assumption was that "breeder reactors would be technically and environmentally feasible by the year 2010 (Nordhaus, 1974, p. 25)[7]." This would now be classed as an unrealistically optimistic assumption. This example illustrates how difficult it is to predict substitution possibilities and technological change. An aim of this thesis is to develop a model that analysis possible restrictions on substitutability. As explained in later chapters energy analysis is a possible method of achieving this. The key reason energy is important is that it is impossible to totally substitute other things for it.

1.8 Conventional macro-economic model

The standard macro-economic model presented in most economic texts is of little use when analysing possible physical restrictions to the economy (Peet, 1992, Daly, 1991). This macro economic model is illustrated by the closed loop flows between consumption and production (Figure 4-1). Daly is critical of this method of analysis of economic flows:

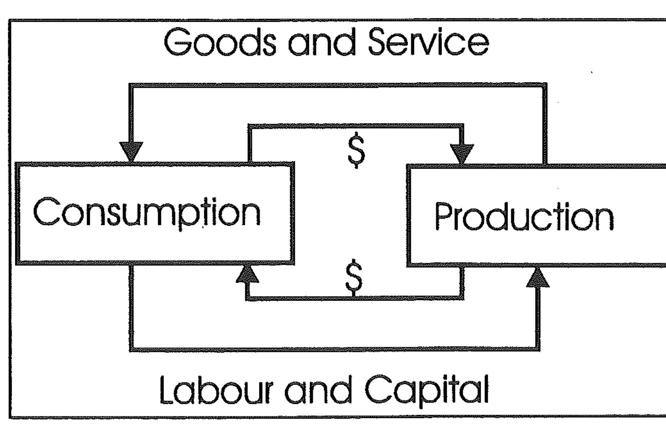

***Figure 4-1** Closed loop flows between consumption and production in a conventional macroeconomic model.*

> Studying an economy in terms of the circular flow without considering the

throughput is like studying physiology in terms of the circulatory system without ever mentioning the digestive tract (1991, p. 196).

This model can be modified to show the flows of resources from the environment or the pollution output from the economy into the environment. However, the model still does not offer many insights in this form. Gilliland (1977) was one of the first to explicitly include different types of resource flows into the conventional macro economic model. The aim of her model was to show the importance of fuel driving the production system. Physical flows between the environment and the economy are further split in Chapter 7 so that a dynamic model of the physiology of the economy-environment interface can be built.

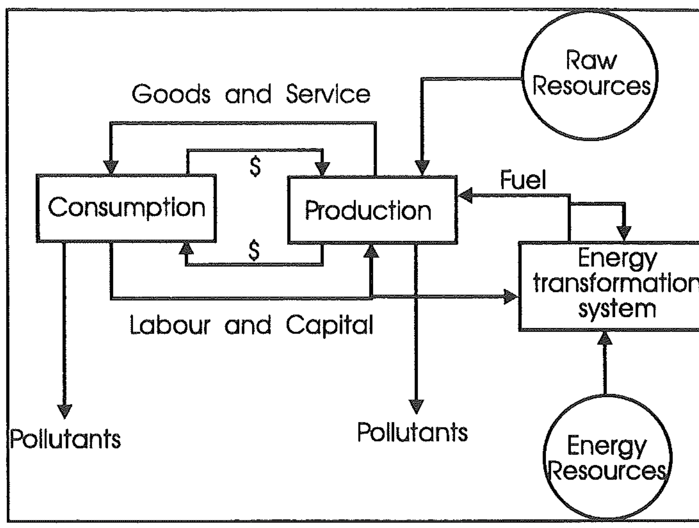

Figure 4-2 *Gilliland's economic model*

1.9 Econometric models

Econometric modelling is the most common form of macroeconomic modelling. It is important to discuss the purpose of these models and how they differ from the physical economic model developed in this thesis. Because of the different purposes, the models are not necessarily contradictory, but may be complementary; the question is in what way each may be helpful or limited in its usefulness.

Econometric models are a step up from simple time series analysis of data which was the main method of analysing the economy until the 1930s. The models aim to link important factors together based on cause and effect. The modelling approach allows the effects of policy and external effects to be estimated. This cannot be done by analysis of time series alone. Some key information and points of interest in large econometric models include: prices, wages, property income, transfers, fiscal policy, monetary policy, financial markets, interest rates, credit flows, unemployment etc. (based on the Wharton economic models in Klein and Young, 1981, p. 19). The aim of these models is to predict the major economic indicators over a short to medium time (3 months to 5 years). The theory behind an econometric model is based on the idea that a careful analysis of historical data can be a good starting point for analysing or projecting the future (Werbos, 1990 p. 214).

What defines an econometric model is not so much its structure but how information or parameters are obtained to plug into the models (ibid, 1990). A large body of knowledge on the best statistical methods for finding parameters for these models has been built up. An example of the type of relationship that is significant is that between demand for products and their prices; this is defined as the elasticity. For example, a negative 0.3 elasticity means that a 10% increase in energy price will cause a 3% decrease in energy demand. From estimates of changes in GNP and changes in the price of energy the changes in demand for energy can be forecast. Essentially these are models of human behaviour, ie how humans behave to changes in price.

It has been found that this type of model is not very accurate for long term predictions (Sterman, 1991, Leontief, 1982). Prices, elasticities and growth rates cannot be predicted in the very long term. The form of the econometric model is not convenient for displaying the structural detail of economic systems (Betz and de Azevedo, 1976, p. 39). It is assumed the input-output structure is the same in econometric models and this is a reasonable assumption for the designed period of the analysis (Klein and Young, 1981, p. 24). Because of the limited information on structural change Lapillonne and Chateau suggest that their use should be restricted to forecasts for a period over which the effects of structural changes can be considered as marginal (5-10 years) (Lapillonne and Chateau, 1979, p. 331).

The focus of this thesis is the dynamics of economic growth and how critical physical resource (energy) use changes over time. Schipper and Meyers believe that econometric models offer little information on this question:

> The relationships that are found between energy use and energy prices, for example, usually reveal little about the underlying dynamics of change in energy use. The physical nature of energy use - the interaction between people and a diverse set of changing technologies - is not well captured by most macroeconomic modeling. Moreover, one does not get a sense for how much the energy efficiency of particular end uses might change, of what the impact of specific policies might be (Schipper and Meyers, 1992, p. 55).

The problem with conventional econometric methods of economic forecasting is that they do not include any physical or technological information which are the key long term determinants of long-term economic growth. It is only from these physical indicators that we can hope to understand possible long term restrictions to economic growth. The relationship between econometric and physical models is discussed further in Chapter 12.

2 Discussion of conventional economics

Modern criticisms of conventional economics are very similar to those of the early ecological economists. For example, Christensen thinks that:

> ..mainstream and organisation economics lacks any explicit specification of the materials, energy, and thermodynamic pathways which are central to an economic "physiology" and a fuller understanding of technological process and dynamics (Christensen, 1994)

Other problems with economics relate to how the economic output is measured and the rationale on which market economics is based.

2.1 Measuring economic output - Quality of life

How should economic output be measured? The conventional method is Gross National Product (GNP) which is defined as "The value, at current market prices, of all final goods and services produced within some time period by a nation" (Samuelson and Nordhaus, 1989 p. 973). Converting this GNP to constant dollars, to account for inflation, means that this is a dimensionless index of the quantity of economic output.

A clear distinction should be made between the GNP, the materials-energy throughput and the quality of life (Ekins and Jacobs, 1994). This thesis investigates the extent to which GNP and material-energy throughput are linked. The links between material well being (GNP) and quality of life are much more subtle and difficult to define.

> The true product of the economic process is an immaterial flux, the enjoyment of life, whose relation to the entropic transformation of matter-energy is still wrapped in mystery (Georgescu-Roegen, 1976, p. xiv)."

Economists have long maintained that growth of GNP is quite distinct from happiness or improvement in the quality of life (Freeman, 1992) although it is the one indicator that governments strive to increase. Trainer believes:

> We should only ask whether the development in question will improve the quality of life, and it should be of little consequence whether it raised or lowered the GNP (Trainer, 1990, p. 280).

This is, of course, a much harder subjective question. Galbraith (1958) suggests that many current wants are artificially induced by advertising. From this one can assume that it would be possible to significantly reduce GNP without affecting the quality of life. If this is true then the physical restrictions on increasing GNP may not be as harmful to quality of life as some would suggest.

2.2 Economic rationality

The previous sections have described the mainstream economic approach to solving any resource or environmental problems. The market mechanism on which economics is based, is assumed to be value free and it delivers only what people want. Individuals are free to make decision to maximise their "utility." From this is it is often assumed that peoples' wants are unlimited, from which follows the desirability of an ever-growing economy. This economic rationality is however not a universal trait of human nature. Anthropologists have studied the reasons why some cultures do not seek a growing economy (in: Perrings, 1987, p. 144) . Perrings suggests that the reason some cultures used the same technology for thousands of years is not because of sloth but to maintain environmental resources (Perrings 1987 p. 144). Sahlins (1974, in: ibid. p. 145) goes on to say that:

> ...households that are more productive than the average, by reason, for instance, of the position in the family cycle, will tend to produce below capacity to avoid creating social tension (ibid. p. 144).

Godelier (1972, p. 290 in: ibid. p. 145) suggest that this is perfectly rational behaviour, though the rationality of such systems should not be mistaken for the individualistic rationality of "economic man." Rationality is culturally and time dependent. This point should be remembered when arguments are dismissed as economically irrational.

3 Conclusions

This section briefly outlines the main points of debate between conventional economists and ecological economists. There is a wealth of literature that details these differences in more detail (Daly, 1991, Jansson, 1994, Costanza, 1991a). Economists seek to measure human values and provide a system such that these values (utility) can be maximised. However, no analysis of human behaviour will be able to determine physical limits on economic growth as it is physical flows that interact with the environment. Physical limits are related to physical flows, ecosystem feedbacks and technology change; hence these are the main topics of analysis in the following chapters.

Notes

1. However, it is difficult to know if this response will totally "fix" the problem.

2. A zero interest rate assumes consumption in the future is valued as highly as present consumption. Positive discount rates assume future consumption is less valuable.

3. A notable exception to this trend is forestry products.

4. It is however very difficult to draw conclusions from this data due to the changing structure of the USA's economy. The trade balance of resources may have had a significant effect on the resources produced in the U.S.A economy (Hall et al., 1986).

5. It could be argued that the point of economic analysis is to put a number on the scarcities but this still does not do anything more than reflect how scarce people *think* a resource is.

6. The second of these sentences has been quoted by itself by a number of authors (Daly, 1994, p. 22, Hall et al., 1989, p. 77). This totally distorts Solow's views as he does not automatically assume all resources are substitutable.

7. This was a common assumption in energy models of the seventies. For examples see: Kavanagh (1979).

Chapter 5: Non-physical aspects of sustainable development.

The aim of this thesis is to clarify some underlying factors that may limit economic growth. The models developed in the following chapters focus on physical restrictions to economic growth, but as outlined in Chapter 3 there are several nonphysical or ethical limits on economic growth. The first part of this chapter clearly defines the difference between physical and ethical decisions while the rest of the chapter outlines some of the key ethical problems surrounding the concept of sustainable development.

1 The difference between physical and nonphysical limits

The difference between physical and ethical limits on the economy is best illustrated by way of a simple example. Suppose a development proposal will make a species[1] extinct and it is proved beyond doubt that this species is not required for the functioning of the ecosystem. In this case the physical facts are agreed upon and it is only the ethical decision of how much the species is valued that is contentious. It is a different type of question to ask, not: is it true? but: does it matter? How can we decide which of two opposing value judgements is the right one? Scientists cannot help us here. Deciding what ought to be the case is quite different from determining what is the case (Monro, 1980). No physical modelling will resolve this.

In the above example the difference between physical and nonphysical limit is clear, but it is not always so clear. Take, for example, a development proposal that will deplete a local resource. In this case assume there is ethical agreement that future generations are important. However there is disagreement over beliefs of what will happen in the future. One side believes that using up the resource will mean that there is none left for future generations so the resource should be used only sparingly. The other opinion is that making use of this easily accessible resource will allow a faster development of society that will leave future generations in a better position to find possibly better alternatives. In this case a physical model may help clarify the options by looking at trends in technological change and resource availability. The other role of a physical model is to identify the contentious facts, the uncertainties and risks involved in a development proposal.

Many problems relating to sustainable development are disagreements about both facts and values. For example with the enhanced greenhouse effect there is no agreement on whether it is going to happen and no agreement on how much it matters if it does happen (see Nordhaus, 1990). This makes policy decisions particularly difficult.

The point of these examples is to stress the difference between ethical and physical restrictions on the economy. Wherever possible throughout this thesis the physical and ethical problems are separated as they require different approaches, just as the different physical questions identified in Chapter 3 require different approaches. There are numerous methods of resolving ethical and moral dilemmas but it is beyond the scope of this thesis to analyse them. Some important ethical dilemmas are highlighted in the rest of the chapter, to put the physical model developed in this thesis into perspective.

2 Ethical restriction on the economy

It seems likely that many policy decisions surrounding conservation and the environment are ethically driven rather than physically driven. As example of this is the ban on whaling. Some species of whale are no longer threatened by extinction and could be sustainability harvested. It is only the ethical opinions of a majority of countries that ensures the ban continues[2].

The main ethical questions that may lead to limits are:

Do we have a right to risk ecological destruction?

Do we have obligations to future generation?

Do other species have rights to exist?

Perhaps the most difficult question is: How should ethical questions be resolved?

2.1 Meta-ethical question. Who should decide?

How should ethical questions be resolved? This is a major ethical question in itself, as the answer will influence how all ethical dilemmas are resolved; hence it is a meta-ethical question. Ideally, ethical decisions should reflect the ethical position of the community the decision will affect. Ethical decisions are usually made by governments. For example, the government will decide any policy for species conservation. If it is a democratically elected government, it will hopefully reflect the majority of the population's views. The difficulty with this is whether humans have the right to decide the fate of other species. Even the most democratic voting system is not very democratic if you happen to be a nonhuman species. Take for example the possible extinction of the giant panda. It may be proven beyond doubt that this would have no negative effects on the rest of the environment (physical question). It may also be decided unanimously around the world that we do not really want or need panda bears (ethical question). Would it still be ethically correct to make panda bears extinct? If the answer is no then how are ethical restrictions on human behaviour be resolved? If we can't decide democratically how do we decide?

Giant pandas were used in the example above because of the emotional attachment that is common. Many people do not want pandas to become extinct. The same question could be asked about an insignificant species of fly. Would the answer be the same? If not, then what is the difference? What right do we have to decide the fate of a species? It is one ethical question to ask, should we make a species extinct. It is another question altogether to ask if we have the right to make that decision. A well informed democratic process is perhaps the only fair way to decide on ethical dilemmas. It is important that specialists such as engineers, planners, ecologists and economists recognise not only their incapacity to determine ethical decisions, but also the legitimacy of the political process to decide social priorities (Checkland, 1981, p. 132).

2.2 Other species

One way of viewing the ethical problem of inter-species equity is to imagine if the roles were reversed. Imagine a species, perhaps an extraterrestrial species, who are incomprehensibly more intelligent and have a "level of being" higher than our consciousness. They decide they like our planet and colonise it without regard for us. There is no way for us to outwit them. We have to rely on their ethical value that the human species has some right to exist. This brief example illustrates how ethical problems may be resolved and debated.

2.3 Risk and uncertainty

There is an important difference between risk and uncertainty. With risk the chance of events occurring is known. With uncertainty the chance of events occurring is unknown. Costanza suggests that: "Most important environmental problems suffer from true uncertainty, not merely risk (Costanza, 1992, p. 13)." It is important that the uncertainties are stated explicitly and better communicated.

2.4 What sorts of "risk" and "uncertainty" are we willing to create or live with?

Uncertainty is a part of life that cannot be avoided. The aim is not to eliminate it but to make decisions based on a clear understanding of the uncertainty involved. It may be that the human species collectively decides that it likes to take risks. Is it more desirable to go fast and out of control or slow and in control? This is not a physical problem but a sociological/ethical question. Georgescu-Roegen summed up this dilemma:

> Perhaps, the destiny of man is to have a short, but firey, exciting and extravagant life rather than a long, uneventful and vegetative existence (1976, p. 35).

2.5 The role of paradigms

Kuhn's (1962) book, "The structure of scientific revolutions" highlights the importance of paradigms in changing scientific and social views. The sociologists Catton and Dunlap (1978) draw on Kuhn's work to define different environmental paradigms. They identified the "Human Exceptionalist Paradigm" and the "New Environmental Paradigm." The characteristics of the two are listed as follows:

The "Human Exceptionalist Paradigm"

> -Humans are unique among the earth's creatures, for they have culture.
> -Culture can vary almost infinitely and can change much more rapidly than biological traits.
> -Thus, many human differences are socially induced rather than inborn, they can be socially altered, and inconvenient differences can be eliminated.
> -Thus, also, cultural accumulation means that progress can continue without limit, making social problems ultimately soluble.

The "New Environmental Paradigm"

> -Human beings are but one species among the many that are interdependently involved in the biotic communities that shape our social life.
> -Intricate linkages of cause and effect and feedback in the web of nature produce many unintended consequences from purposive human action.
> -The world is finite, so there are potent physical and biological limits constraining economic growth, social progress, and other societal phenomena.

The conclusions coming out of the environmental paradigm potentially change our understanding of our role in the world. Dunlap notes that:

> By disputing the notion that humans are unlike all other creatures and largely exempt from the laws of nature, the ecological paradigm-like the Copernican and Darwinian paradigms before it - challenges humanity's view of its place and role in the universe (Dunlap, 1981, p. 205).

As with any significant paradigm change it will take a long time to become generally accepted. The paradigm people choose determines whether one is in favour or against protection of species and the environment. Unless the core differences in paradigms are identified, it is possible to talk past each other without understanding the other's views.

The Ehrlich-Simon debate is a good example of this (Ehrlich, 1981a, 1981b, Simon, 1981, 1982). Differences in paradigms are noted here because of their influence on *ethical* dilemmas. The paradigms should not affect the *physical* model developed in this thesis.

3 How are ethics applied in the rest of science?

Ethical dilemmas are not unique to environmental problems. Ethics in the medical profession are particularly well developed. There are some interesting comparisons between the ethical system of the medical profession and the ethical system of dealing with the environment. Both cases involve the manipulation and understanding of complex systems that are not fully understood. For the medical profession the complex system is the human body, and for the ecologists it is the ecosystem. The ecosystem as a whole is even more complicated than the functioning of a human body, and is different from the human body in that there is only one whole system, so it is not possible to perform controlled experiments.

The medical profession is ethically restricted because human life is highly valued. The environment is not yet valued as highly. It could be argued that the environment should be treated with the same care as something that is alive, because all life is dependent on its continued functioning. Lovelock (1979) has pointed out some elements of environmental regulation that are similar to the complex homoeostatic control found in living things. Lovelock's Gaia hypothesis is not required to support a high value being placed on the environment, as it is not valuable because it is alive but because life is dependent on it.

We are only prepared to experiment on humans with extreme caution. The same is not true for the earth's ecosystems, because we do not value them to the same extent. Perhaps this situation could be represented by an experiment. Consider a room full of air with one human inside it. A black box controls the air quality[3]. There is no consensus on how the control box works. What rules would govern the tampering with the box? Rules governing experimentation on the box should be as strict as those for experimenting with the person. If this is accepted then rules governing the experimentation with the ecosystem should also be strict.

Waste products from the economy are dumped into the environment without knowing exactly how they will affect it. This is analogous to injecting various substances into the bloodstream simultaneously and only stopping the injecting when it has been demonstrated that the particular substance injected has negative side effects.

Long term testing is done on any new medical process before it is available to the public. The medical profession has to "prove[4]" there are no side effects or only acceptable side effects before new substances can be prescribed. Engineers can virtually do anything they can conceive. If in the long term there are side effects this has to be rigorously proved before the process in question is stopped. It is sometimes assumed that the side effects are too far away for us to bother with and it is assumed that future generations will solve any problems with the side effects. This sort of ethical reasoning is unlikely to be accepted in the medical profession, perhaps because any side effect directly affects individuals.

Applying this precautionary principle to the environment is often argued to be unscientific. For example, Milne states that:

> The views of the conservationists on ecological damage involve value judgements in favour of high-level ecological systems, but implied that these were "scientific" or "objective" (Milne, 1993, p. 78).

This is similar to saying that doctors prefer high-level human systems ie. healthy systems. The essential difference is that ecologists put a high value on the environment because they recognise its link to our own health.

4 Applying ethics to the environment

The ethical values of communities are constantly changing. If the ethical and physical restrictions on the economy cause a decline in economic growth then the ethical position of the community may change. For example, the price of timber may cause a housing shortage. This could be due to ethical restrictions on the amount of forest that must be preserved to keep within a certain risk value for ecological stability. The public may decide that they are willing to increase the risk of total ecological collapse to make housing more available. Presuming the physical information available to the ecologists is the same, the amount of forest available to the economy will increase and the price of timber will decline making housing more affordable. If decisions are made in this way the ethical question being addressed is explicit so it may be openly debated. Presently this type of decision may be made by politicians who may consider all of the ethical and physical questions simultaneously, as well as the effects the decision may have on their political future.

5 Social limits to growth.

Another aspect of limits to growth is the effect that a growing economy has on peoples general well being. It has been argued that economic growth brings more costs than benefits; for example Hirsch comments:

> The concern with the limits to growth that has been voiced by and through the Club of Rome is strikingly misplaced. It focuses on distant and uncertain physical limits and overlooks the immediate if less apocalyptic presence of social limits to growth (Hirsch, 1976, In: Ekins 1993, p. 274).

Social limits to growth may be very significant, however, this is another aspect of sustainability that is beyond the scope of this thesis.

6 Conclusions

This chapter has identified ethical dilemmas that arise from the economy environment interaction. The physical model developed in this thesis does not resolve these ethical dilemmas[5]. It does, however, partially separate the physical and ethical components of the sustainable development problem to clarify the problem. An important function of modelling is to identify the elements of uncertainty and danger associated with a physical scenario of the future so the key issues can be debated rather than clouded together in one huge problem. Resolving the ethical dilemmas outlined in this chapter is a major task for ecological economists but is beyond the scope of this investigation to analyse further.

Notes

1. I purposely have not named a species as this would lead the reader in one direction or the other. A panda bear has a different value to a species of mosquito.

2. Even if it was proven beyond doubt that whales could be sustainably harvested many people would be against this. This should be recognised as an ethical decision, much like the ethical decision of western countries not to eat cats and dogs, rather than a decision to preserve the species.

3. A more realistic example might be a patent who is dependent on a piece of medical equipment (eg heart and lung machine).

4. A proof will never be complete.

5. Some of the exogenous variables in the model are set ethically, so different ethical assumptions can be tested in the model.

Part 2: Developing the theory of a physical model

Chapter 6: System dynamic modelling

This chapter explains the Systems methodology and how this differs from the conventional scientific approach to solving problems. The complexity of sustainable development requires the systems approach.

1 What is good science?

It is a common acception, "scientific method" is taken to comprises the following steps: defining a problem, developing a hypothesis that addresses the problem and then testing that hypothesis by some sort of falsification test. To make the problem solvable a small area of analysis is usually defined. In this sort of science there can be a high degree of control over the system being studied - enabling precise observation of the behavioural correlations between a small number of variables. Waynne and Mayer note that this has: "become equated with 'good science' (Waynne and Mayer, 1993)." Unfortunately the problems associated with sustainable development cannot be so neatly reduced, defined or tested, thus research in this area is often considered less "scientific." Folke et al. call this the:

> "partial quantification trap": They often end up doing in the best possible way something that probably should never be done at all. "Good science" and good academic research need to be redefined as relevant problem solving in the face of whatever level of precision is possible (in: Janson et al. 1994, p. 12)

1.1 Reductionist science and systems science

Traditional reductionist science is not good at coping with complexity. It can only isolate small parts of the total problem to analyse. The systems approach to problem solving is offered as a methodology for coping with complexity. This systems methodology has been developed over the last 40 years and is gaining acceptance in the wider scientific community (Forrester, 1975, Checkland, 1981, Meadows et al. 1992, Sterman, 1992)

Many important questions facing society are inevitably complex and hard to define. Perhaps the importance of the problem increases as the complexity and uncertainty increase. The reductionist scientific method has had little success at solving them. Attempts to solve these problems have been attacked for their lack of scientific rigour. But one must ask: Is the question posed worth answering? Can one think of a better way of doing it?

1.2 Uncertainties and complexity

The complexity and uncertainty of the real word is nicely summed up by Gleick:

> The world makes a messy laboratory for ecologists, a caldron of five million interacting species. Or is it fifty million? Ecologists do not actually know (Gleick, 1987, p. 59).

Ecological economists stress the importance of being honest about and communicating the uncertainties involved in their analyses (Costanza, 1991, Daly, 1991). There is a tendency for elite groups to underestimate the degree of uncertainty in their work (Raiffa, 1968 in: Werbos, 1990b p. 179) because uncertainty is seen as a weakness or failure to understand the problems. Uncertainty should be seen as a strength rather than a weakness (Alldrift, 1977). "Instead of the classical view of science eliminating uncertainty, the new scientific paradigm accepts uncertainty as inevitable (Allen and Peet, 1994)."

2 Why build models?

Anyone who proposes a policy, law, or course of action is doing so on the basis of the model in which he/she, at that time, has the greatest confidence (Forrester, 1971). Normally the model is a mental one that is built up from understanding an experience and it is inevitably fuzzy. The aim of systems model building is to make the assumption and reasoning behind decisions explicit. The model building process can also be used to build consensus among people as the underlying theories have to be expressed explicitly. Differences in assumptions, and policy objectives can also be identified and sensitive parameters can be isolated (Choucri and Heye, 1990). The aim of models is not to predict the future but to gain understanding about the functioning of the system (Sterman, 1992). Models also allow a hypotheses about the behaviourof the system to be explored without having to interfere with the real system. In the case of physical limits on long term economic growth this is the only alternative.

2.1 Types of model

The distinction between optimisation models and simulation models is important. Optimisation models have goals to be met, choices to be made and constraints to be satisfied. Simulation models are different in that they do not generally aim to maximise any one parameter. They are used to test different scenarios to see what might happen if something else happens. Several authors have called this type of model a "what if?" model (Sterman, 1991, Hoffman and McInnis, 1994). The aim is to understand the system not to optimise it.

2.2 The importance of purpose in building models

Sterman thinks that: "the art of model building is knowing what to cut out, and the purpose of the model acts as the logical knife (Sterman, 1991, p. 211)." The purpose of the models in this thesis is to investigate physical limits to growth. Given this purpose, many complex nonphysical aspects of the economy involved with money flows, such as interest rates, profits, discount rates etc. can be removed from the model.

3 Systems dynamics

3.1 Prediction versus understanding

Explicit models of complex problems are often criticised for their lack of prediction (Forrester, 1971) and over simplification. It must be stressed that the aim of simulation models is not prediction. It is not possible to predict the outcome of a simple sporting event let alone the entire economic environment system. Cofala notes that: "Without simplification, the only model of reality is reality itself, and only one experiment is permitted (Cofala, 1990, p. 388)." It is the understanding of significant causal influences that is important rather than exact prediction. The importance of understanding rather than prediction is expressed nicely by Meadows et al.:

> If your doctor tells you that you will have a heart attack if you do not stop smoking, this advice is helpful, even if it does not tell you exactly when a heart attack will occur or how bad it will be. (Meadows, Richardson, and Bruckmann, 1982, p. 279).

The value of a forecast is not whether or not it is right but if it is useful in making a decision (Martino, 1993).

3.2 Iterative process of learning - evolution

The prime value in 'a systems approach' is that it is continuous (Checkland, 1981, p. 285). There is an iterative process from making one's perceptions explicit in a model and then testing their adequacy via simulation. Insights are gained by changing the model and resimulating. Thus the model is never complete, but only in its latest stage of development. Insights are generated by the modelling process and are then reflected in the structure of the model. Thus, the process is evolutionary.

3.3 The importance of structure and level of aggregation

There is a balance between the complexity and simplicity of the model. One can make one's model more complex and more faithful to reality, or one can make it simpler and easier to handle. One must be careful with simplification, however, because ignoring a relationship implies that it has a value of zero - probably the only value known to be wrong (Forrester, 1980)

An aim of system dynamics modelling is to have as many variables as possible calculated by the model structure itself. This is more likely to be insightful than having tables of exogenous variables that are critical to the model behaviour. It is not however possible to have a model that includes everything that is important in the one model. In the New Zealand model developed in Chapter 15 external influences will come from the international economy and unpredictable scientific discoveries. Because of the small scale of the New Zealand economy in relation to the world economy, it would be unrealistic to expect the New Zealand economy to influence these exogenous factors. The best that can be done is to make realistic estimates based on historical trends and other relevant knowledge.

3.4 Model validation

A typical method of model validation is to set the model up some time in the past and simulate to see how well it models that time period. The problem with this is that it is quite possible to get an extremely good historical data fit but the future it simulates is obviously incorrect. An example of a model like this is the energy substitution model of New Zealand by Bodger et al. (1992). The aim of this model is to predict the market share of the various energy sectors in the New Zealand economy. The historical data fit is extraordinarily good. However, if the model is extrapolated into the future it estimates large drops in petrol and electricity demand. This is contrary to almost all other understanding on electricity and petrol demand and seems highly unlikely. It is, of course possible, but not due to the factors in the energy substitution model.

The results of a dynamic systems model should first be compared with what one would intuitively expect to happen. If there is disagreement then the model can hopefully be improved and understanding can be increased. This is how the problems of using Slesser's (1990) ECCO methodology were discovered (see Chapter 13). When the model results did not agree with intuition, the reasons behind it were investigated. Analysing the difference between the computer model and the mental model allows the underlying causes of the differences to be identified and then both models can be improved (Sterman, 1991). System dynamics models force one to explicitly state one's model with causal relations. This can then be tested to check that it makes sense. It causes one to focus very clearly on the key parts of the problem.

Sterman (1984) stresses that there is no absolute test of validity of a model:"Useful," "illuminating" "convincing," or "inspiring confidence" are more apt descriptions applying to models than "valid." Similarly Checkland states that: "There are not valid models and invalid ones, only defensible conceptual models and ones which are less defensible (Checkland, 1981, p. 173). This is a different process from the reductionist scientific model building process where controlled experiments can be used to test the robustness of a model.

Chapter 7: Definition of system boundaries and flows between environment and economy

The first step in building a physical model of the environment and economy is to identify the different types of flows between the two. The purpose of the following system diagrams is to define the system boundaries and to show the important flows and influences between an economy and its physical environment. The aim of this investigation is to define and quantify some of the physical limits that may restrict long term growth of the economy. It is important to accurately define all the terms used in a quantitative physical model. These definitions aim to separate the physically different flows into groups that can be analysed in a similar way. Although they have been designed with dynamic physical models in mind these definitions may be useful for other studies of long term physical limits.

The models developed in the following sections are an extension of the Gilliland economic model discussed in Chapter 4. The model is expanded to include three physically different types of resources. To simplify the following models, flows of money, labour, and goods and services between consumption and production sectors are not shown. For the present, it is the flows of resources and pollution into and out of the economy that are of interest.

The two physical flows that may restrict the growth of an economy are resource inputs and waste outputs. Although this seems obvious, some people deny that we are dependent on environmental flows. For example, Fisher and Peterson say: "Man has probably always worried about the environment because he was once totally dependent on it (1976, p. 1 quoted in: Daly, 1991, p. 125)." This section illustrates that physical flows to and from the environment are still vital for the functioning of the economy.

The solid lines in Figure 7-1 show flows of resources and waste into and out of an economy. The dotted lines represent the influence that pollution may have on resources. Drawing a single line representing the influence pollution has on resources does not do justice to the mind boggling complexity of that influence. An example of this influence is the way increases in carbon dioxide affect the climatic system and in turn affect yields from agriculture[1]. The pollution output from the economy may also affect the resources used by other species but have no direct influence on the economy. This latter environmental influence is a separate ethical restriction on the economy rather than a purely physical limit. A physical model will not help resolve ethical problems other than to make them explicit and separate from physical problems. The uncertainty of current knowledge of the influences pollution has on environmental resources is also an ethical issue of how much uncertainty we are willing to create or live with (see Chapter 5).

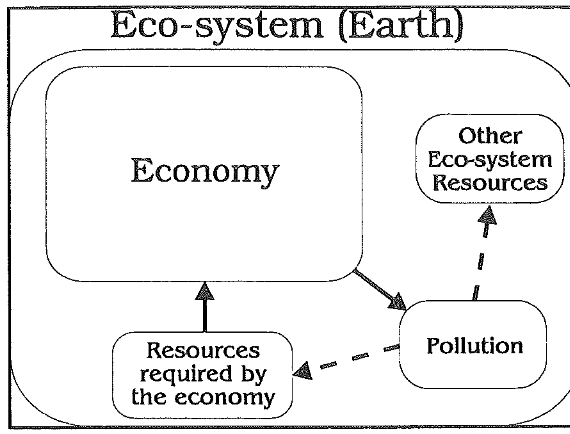

Figure 7-1 Flows and influences between the economy and the environment

1 Definition of different flows between the economy and the environment

Not all resources used in an economy can be treated the same. For the purposes of this study resources are split into three broad types: recyclable, depletable and renewable resources[2]. It should be noted that any splitting of resources into different categories is quite arbitrary and there is a degree of overlap in some cases. The physical properties of these types of resources are sufficiently different for them to need to be analysed separately in a physical economy-environment model.

1.1 Depletable (energy) resources

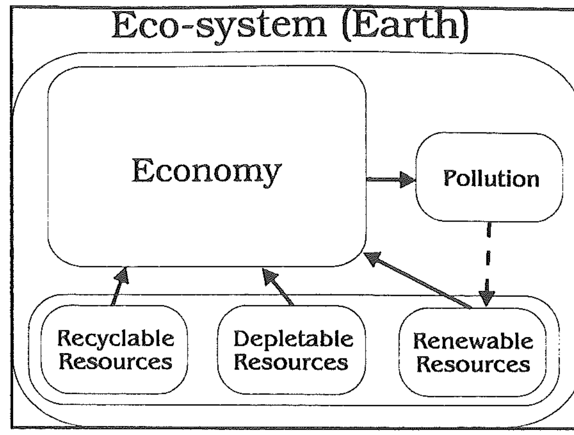

Figure 7-2 *Significant physical flows between the economy and the environment.*

Depletable resources are defined as non-renewable resources used for their energy potential. Oil used as a fuel is depletable because its energy potential is irrecoverably dissipated after combustion. The combustion products from a fossil fuel can in theory be returned to their original state but this would require more energy than the energy gained by combustion. This would be a pointless exercise if the oil is to be used for that energy potential.

Oil used for lubrication or any other non-energy purpose is not defined as a depletable resource. In the case of lubrication it is the viscous properties of the hydrocarbons that are significant. Given enough energy these can be reproduced. To put it another way, the hydrogen and carbon that make up oil are recyclable, but the energy potential of their chemical bonds is irrecoverably lost on combustion. The fact that high quality energy is irrecoverably lost on combustion means that energy is significantly physically different from other resources used in the economy. This factor is discussed in more detail in the following chapter.

According to the definition above the only depletable resources used in the economy are fossil energy resources. Renewable resources are potentially depletable but this is physically different from the irreversible depletion of energy[3].

1.2 Recyclable resources

Recyclable resources include metals and resources such as chemicals and building materials. All non-energy mineral resources are potentially recyclable. They do not get "used up" as the fossil energy resources do. Even a piece of iron that corrodes can in theory be turned back into the original piece of iron by collecting every speck of rust and processing it back into iron. This would be very energy and time intensive task but it could be done in theory.

Georgescu-Roegen believes matter is subject to the second law of thermodynamics and that materials are "irrecoverably dissipated." He refers to this as the fourth law of thermodynamics (Georgescu-Roegen, 1976). This is only partially true. Iron that rusts goes from a high energy (low entropy Fe) state to a lower energy (high entropy Fe_2O_3) state according to the second law of thermodynamics. The iron is not irrecoverably dissipated; it is the energy that was required to reduce the iron from iron oxide that is lost. So it can be said that all other physical resources can always be made available given enough energy (Slesser, 1990, Bianciardi et al., 1993). Matter cannot be destroyed. It can only be transformed by energy (Odum, in Daly, 1991).

The total ecosystem is an example of complete recycling of materials. It is highly debatable whether human systems of resource flows in the economy will ever reach the complexity of homoeostatic control achieved by ecological systems. Often recyclable resources, such as copper, are said to be depletable. However, the total quantity of copper on earth is constant. It is the amount of effort required to make it available for human use that changes when these resources are used. For many practical situations recyclable resources will not be able to be recovered due to the effort required. An extreme example of this may be ink that has been dispersed in the Pacific Ocean. Because 100% recycling is not practical, further resource mining is likely. In general, when mining, the most easily accessible resources will be used first. Resource availability is discussed further in Chapter 13.

1.3 Renewable (ecosystem) resources

Renewable resources include air, land, water, plants, animals etc. The availability of renewable resources is restricted by the flow of solar radiation to earth. These resources are 100% "recycled[4]" by natural solar radiation without human intervention usually over a long period of time (Odum, 1976). A natural ecosystem recycles all elements driven only by the solar flux[5].

Although the individual chemical elements in the biosphere cannot be depleted, the "richness of pattern" can be depleted. Examples of this include species extinction, and local habitat extinction and possibly changes in climatic patterns. According to current scientific knowledge the loss of a species is irreversible. Renewable resources are potentially depletable or conditionally renewable. These resources can be depleted if they are used at a rate greater than the regeneration rate. It is not the atoms of the resource that are lost or the energy potential of their bonds but it is the "richness of pattern" or "structural function" that is lost. This richness of pattern and structural function can take many forms, from individual species to the complex interactions of ecosystems that produce our food (nitrogen carbon, and water cycles). This type of depletion is much harder to define than the depletion of energy resources, but it is important that the distinction between the two types of depletion is made.

Renewable resources can be affected by waste flows from the economy. This feedback is represented by the dotted line in Figure 7-1. These renewable resources are probably the most important resources due to their life supporting function and vulnerability to pollution. Depletable and recyclable resources have only recently been used in significant quantities. It is possible to live without the depletable and recyclable resources but the same is not true for renewable resources.

1.4 Waste/Pollution

For the purpose of our system waste is defined as any physical flow from the economy to the environment. The types of physical waste output can be categorised into the following: inert, biodegradable, recyclable and polluting.

In the very long term all waste is potentially biodegradable. The environment can assimilate waste in small quantities. If the concentration is too high, biodegradable waste can become a pollutant. The rate of waste that can be emitted to the environment is related to the time required for the environment to absorb that waste. Waste is defined as polluting if it has a disturbing influence on the environment. This is a broad definition that can include many different effects. Some waste from the economy is inert and although it is not broken down it may not interfere with the environment. A discarded piece of concrete may be an example of this. Obviously there is also a large potential for recycling waste from the environment back into the economy.

There is a large degree of uncertainty about which category each type of waste would be filed under. For example, until recently carbon dioxide was considered inert. But although carbon dioxide is relatively chemically inert it may significantly affect climatic patterns. According to the definition above, carbon dioxide would be defined as polluting.

2 Resource and waste transformation systems

To analyse the interactions between the economy and the environment, the economy can be split into different sections that interact directly with the environment. The section of the economy that has no direct interaction with the environment is defined as the "main economy" and includes the following sectors: industry, services, transportation, and a domestic (households) sector. This is the part of the economy that provides most of the goods and services to the population. The sectors that interact directly with the environment are defined as the resource and waste transformation systems (Figure 7-3). Once again there is some overlap between the sectors[6].

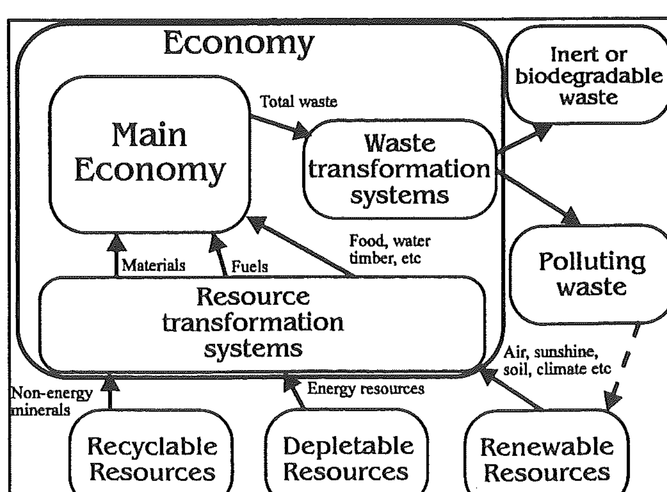

Figure 7-3 Resource and waste transformation systems

Resources provided by the environment often cannot be used directly until they are converted into a usable form. In their natural state resources are not useful inputs to the production process (Cleveland, 1993). Energy resources are converted into fuels. Recyclable resources are converted into useful materials by mining and refining. Renewable resources such as air, sunshine and soil are transformed into products such as food, drinkable water and timber. The amount and type of waste emitted to the environment can be changed using waste control systems. All these transformation systems are defined here as "environmental services." These systems are the interfaces between economy and environment.

The size of the "environmental services sectors" is determined by the demands of the main economy and the physical limits of the particular resources or pollution. The size of "environmental services" relative to the main economy is likely to change over time. Historically the size of these sectors was large relative to the rest of the economy (mainly the agricultural sector). Changes in technology and resource availability will influence their size. The relative size is an indicator of the importance of the environment on the functioning of the economy.

The resource transformation systems are split to deal with the three different types of resources identified. The systems are a material transformation system, an energy transformation system and life support systems.

2.1 Energy transformation system

Energy transformation systems convert fossil resources and renewable resources into fuels that are usable in the economy. Examples of this include electricity production from hydro-power stations and petroleum refining (Figure 7.4).

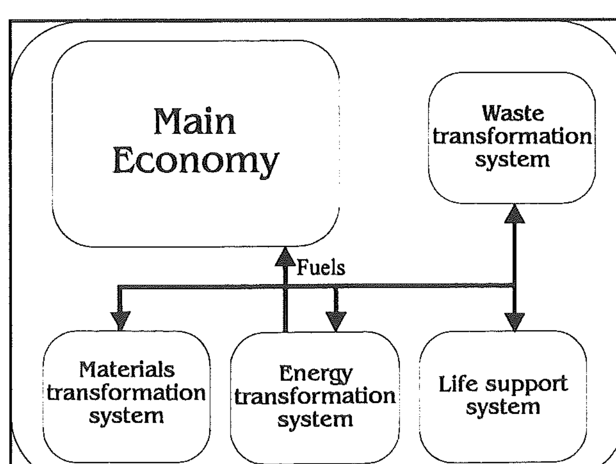

Figure 7-4 Energy transformation systems

These are key sectors for the long term sustainability of an economy. Energy is a physical measure of the effort required to achieve a transformation (see Chapter 8). If there is enough energy produced then it is possible that material standards of living will be high, recyclable resources will always be available, agricultural yields will be high and pollution control may be possible. If, for some reason the fuel flow to the main economy is restricted this could limit the ability of the economy to grow.

2.2 Material transformation system

The material transformation system converts minerals into materials that are usable in the economy. Examples are the smelting of metals and mining of phosphates. Over time the amount of energy required to retrieve a material will change due to changing technology and changing resource scarcity (see Chapter 11)

2.3 Renewable resource transformation systems

Renewable resources are used directly (eg air and sunshine) or converted into useful products such as food and drinkable water. Examples of renewable resource transformation systems include agriculture, forestry and fishing. The size of this sector is dependent on the human population, the level of consumption, availability of land, pollution and the energy available to increase production per unit of land.

2.4 Waste transformation systems

All economic systems produce waste. It is possible to convert waste into useful materials (recycling) or fuels (eg landfill gas). All of the other materials will be emitted to the

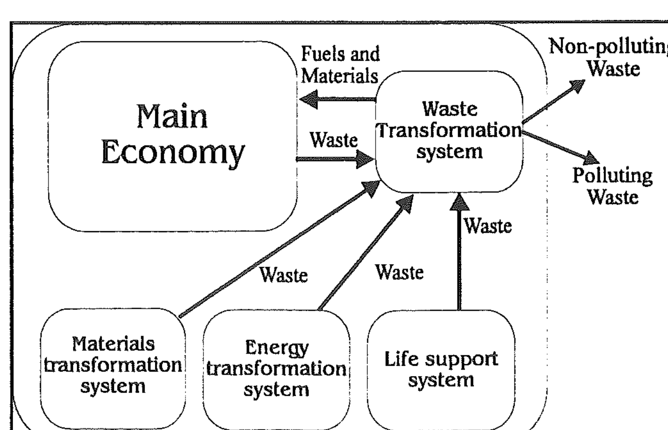

Figure 7-5 Waste transformation systems

environment in some form. Some of this may be inert or biodegradable and therefore may not affect the renewable resources. The relative size of the waste transformation system will change over time as our knowledge of the effects of pollution increases. New technologies may also change the relative size of the waste transformation systems.

3 Industrial output required to maintain environmental services.

Physical flows of goods and services from the "main economy" are required by the environmental services sectors. These goods and services are required to maintain and replace the machinery required to carry out the transformations in the energy, agriculture, materials and waste transformation sectors. A certain quantity of industrial output is also required to maintain industrial growth and to provide consumption goods. If the demand for industrial output in the "environmental services" increases too quickly, this could limit the quantity of industrial output available for reinvestment. Therefore, this could limit the ability of the economy to grow. The dynamics of this are analysed in Chapter 9.

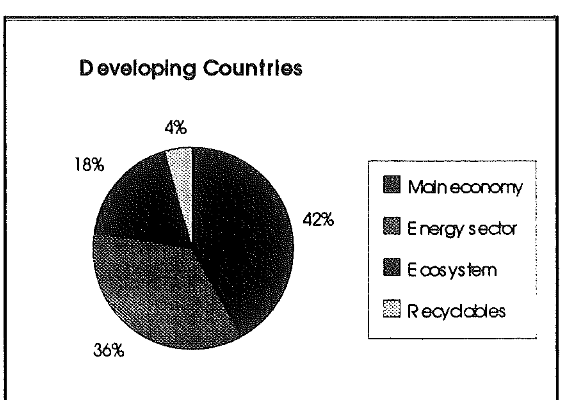

Figure 7-7 *Proportions of economic output from different sectors in developing economies*

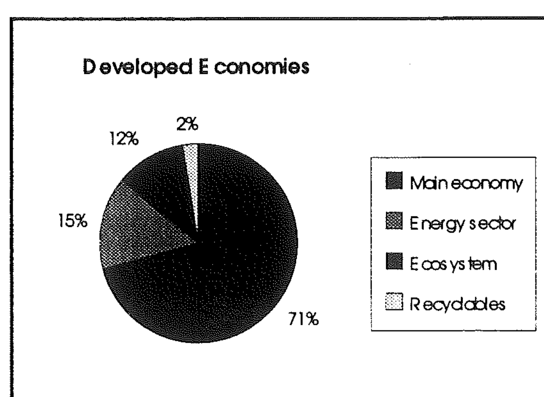

Figure 7-6 *Proportions of economic output from different sectors in developed economies*

The graphs in Figures 7-6 & 7-7 show the relative importance of the different sectors in developing and developed economies around the world[7]. As economies become more developed, the fraction of economic output that comes directly from the environmental services sectors decreases. One of the aims of this analysis is to determine whether this trend can continue in the very long term.

4 Summary

Flows between the main economy, environmental services and the environment are summarised in Figure 7-8. Inputs from the environment to the economy are split into depletable, recyclable and renewable resources. Each type of resource has different physical characteristics. Resources supplied by the environment are converted into useful materials, fuels and agricultural products by the resource transformation systems. Waste may also be transformed into a more desirable form so that is does not have a polluting effect on the environment.

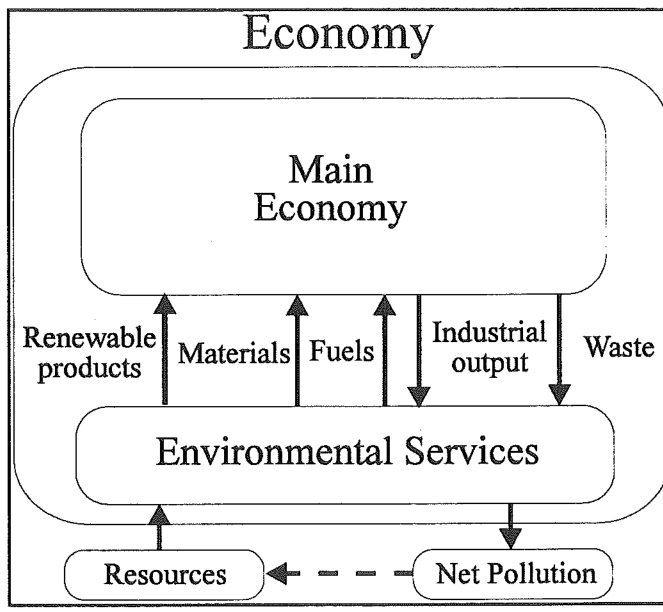

Figure 7-8 *Summary of the physical flows and influences between the economy and the environment*

The key sections within the economy that interact with the economy have been identified (resource transformation systems and waste transformation systems). The relative size of these systems will change over time due to resource depletion, new technology and increased knowledge of the environment. A possible limiting factor in the long term growth of the economy is that these systems may require more industrial output to supply the same services to the main economy. The result of this may be that there is less industrial output available for consumption and reinvestment, thus limiting the growth of the economy.

Notes

1. These influences are discussed further in Chapter 11.

2. This is similar to the definitions proposed by Slesser (1990) of depletable natural capital, renewable capital and recyclable natural capital.

3. In theory species extinction could be reversed in the very long term through evolution. The same is not true for the increase in entropy of a system.

4. Land is not 100% recycled; there are important irreversable processes of nutrient flows, erosion etc.

5. It has been argued by Mansson (1994) that biological systems are Open systems (i.e open to mass as well as energy flows). This is true of individual biological systems but not for the whole biosphere (Bianciardi 1994)

6. For example, a catalytic converter on a car would be defined as a waste transformation system but the car would not.

7. This world data is based on UNIDO (1993) and FAO (1993). The data was not aggregated enough to determine the size of waste control systems.

Chapter 8: Energy Analysis

As identified in the previous chapter energy has sufficiently different properties from other resources to make it worthy of special attention. Energy has also been identified by many other authors as a key factor for analysing physical limits of economic growth (Slesser, 1990, Odum, 1971, Constanza, 1979, Peet, 1992, Hall et al. 1992, Faucheux, 1993). The aim of this chapter is to clarify the role of energy analysis in understanding the flows between the economy and the environment. Energy analysis provides a physical analysis to complement an economic analysis. It has been noted by Peet et al. (1987) that net energy analysis can determine the point of futility for some types of economic exercises. The arguments developed in Chapter 10 show how energy analysis may also be useful for analysing technological development issues.

1 Energy definitions and the laws of thermodynamics

The first law of thermodynamics states that energy can never be created or destroyed. It follows from this that all energy transformations are 100% "efficient" on a first law basis, so strictly speaking there can never be an energy crisis. However, some forms of energy are more useful to us than other forms. The second law of thermodynamics or "entropy law" states that the energy transforms from an ordered state (low entropy) to a less ordered state (high entropy). We value low entropy forms of energy more than high entropy forms as it is possible to do more with the low entropy forms of energy. Specifically, more "work" can be achieved with high quality (low entropy) energy than with low quality (high entropy) energy. It is worth noting that a human value judgement is required to compare the different qualities of energy (Chapman and Roberts, 1983) so there can never be any absolute measure of the quality of energy (see section 5.1).

When the word "energy" is used every day, it refers to high quality energy. There are many technical terms for high quality energy including exergy, negentropy and availability. Negentropy is used in this thesis to refer to low entropy or high quality energy when it is critical for the development of an argument. Otherwise, the word energy is used in its everyday sense.

2 Why is energy an important input to the economy?

What makes energy more significant than any other input to the economy? Benhaïm and Schembri (1994) define the characteristics of a resource that may hinder economic growth in the following way:

> ".. its supply is limited, it is non-renewable and non-recyclable, it is essential, there is no substitute and it is impossible to develop a substitute, and finally it is impossible to improve efficiency over a certain point (1994, p. 601).

Energy (or negentropy) is the most obvious resource that meets these conditions. Fossil resources are limited by the stock available and solar energy is limited by the flow available. All negentropy is non-recyclable (see Chapter 7) and the main sources of energy in the present world economy are also non-renewable. The second law of thermodynamics tells us that high quality energy (negentropy) is an essential non-substitutable requirement for any physical activity. It follows from this that there is a minimum energy requirement for any particular activity in the economy. There is a possibility that labour and a stock of physical capital could produce systems to provide virtually limitless energy but this is a hotly debated question (Odum, 1976, Slesser, 1990, Pimentel et al. 1994). The importance of inexpensive energy in noted by Bostian:

> Once we start producing extremely low-cost, clean, virtually limitless energy, incredible opportunities to expand the world economy will open up (Bostian, 1992).

However, Bostian's optimism about the inevitability of this discovery is questionable. The theory and simulation model developed in this thesis aims to give insights into just this sort of question. The analysis of resource limitations on economic growth by Goeller and Weinberg emphasises the importance of energy:

> Our technical message is clear: Dwindling mineral resources in the aggregate, with the exception of reduced carbon and hydrogen, are per se unlikely to cause Malthusian catastrophe. But the exception is critically important; man must develop an alternative energy source. Moreover, the incentive to keep the cost of prime energy as low as possible is immense. In the Age of Substitutability energy is the ultimate raw material. The living standard will almost surely depend primarily on the cost of prime energy (Goeller and Weinberg, 1978).

The common opinion among economists is that long term energy prices are likely to increase (Carr, 1994). This prediction, together with the non-substitutability of energy, makes it of special interest within the economy. Energy economics is now a recognised specialisation within economics (Common, 1988). The other significant features that make energy of special interest are that new energy projects usually have long lives and long lead times. "Mistakes" in energy decisions have the potential to significantly affect economic performance.

Many major pollutants such as carbon dioxide, sulphates, and particulates are directly related to the use of energy. These pollutants have been identified as potentially destructive to the ecosystem, making energy an even more critical factor in long term economic analysis. A number of authors considers energy can be a good first order indicator of environmental impact (Brown and Herendeen, 1995, O'Connor, 1991, Faucheux et al. Chap 7, 1995) .

2.1 Are we running out of energy?

Schipper and Meyers (1992) sum up the problem with energy and sustainable development:

> Civilisation is not running out of energy resources in any absolute sense, nor running out of technological options for transforming energy resources into the forms our patterns of energy use require. What is running out, rather, is the capacity to expand energy supply at low cost - a capacity which is fundamental to the growth of material wealth in today's industrial nations (Schipper and Meyers, 1992, p. 1)

Similarly, Smil (1992) and Zucchetto (1994) do not think running out of energy is as significant a factor as environmental and social constraints which will probably increase the cost of energy.

2.2 Energy as a measure of scarcity

Scarcity is an extremely complex phenomenon that is determined by many biophysical and social variables. The discussion in Chapter 4 shows the problems of using price as a measure of scarcity. Analysts who use a single index to deduce the trend in scarcity make the critical assumption that all the relevant forces that increase or decrease scarcity are embodied in that index (Cleveland, 1993). Energy is only a biophysical indicator of scarcity and should always be used in conjunction with other measures.

In a sense energy is a "master resource" in that energy can relieve other resource scarcities (Cleveland, 1993). The basic reason for using energy as an indicator of scarcity/accessibility is based on the arguments of Chapman and Roberts (1982). Energy requirement is a technical measurement common to all processes. Furthermore the energy requirement is a measure of the physical 'difficulty' of bringing about the transformations in the process[1]. A process that has a larger energy requirement is 'physically more difficult' to accomplish. The energy requirement could be used as an index of the technical costs of accomplishing the transformation. In the long run, the trend in production costs determines accessibility and is reflected in the trend in prices. If valid this means that future accessibility can be estimated by calculating the fuel required for producing goods and services in the future. This can be done more reliably than estimating the future prices of goods and services, since fuel use in the future is dependent on technical and thermodynamic factors.

The energy requirement only measures the technical cost of producing a good or service. The price will be determined by factors that affect supply and demand in the marketplace. An example is the price of oil that does not reflect the almost constant technical cost of supplying oil. Short term price fluctuations are influenced by social and political factors (Chapman and Roberts, 1982).

2.3 Energy theory of value

Using energy as a measure of resource scarcity is often mistakenly linked with an energy theory of value. An energy theory of value states that the "true" value of goods is proportional to the total energy required to make them. This idea has a long history going back to the Technocracy Movement of the 1920s and before (Ostwald, 1910 and Soddy, 1926. in: Martinez Alier, 1987). The Technocracy Movement, founded in 1920 by H. Scott, was the first significant organisation to promote an energy theory of value (Scott, 1933. in: ibid). They wanted to replace the price system with a system of energy valuation and energy coupons. This movement died after the second world war but it has been reoccurring among engineer-economists (Hannon 1975, Slesser 1992, Odum, 1976). Odum argues for the use an energy theory of value in the following way:

> Since the energy involved in work is an unchanged measure of what has been accomplished, energy is found to be the best measure of value. (Odum, 1976, p. 55).

Like any theory that considers one input important above all others, the energy theories of value fails to adequately describe the entire economy. Constanza's (1980) analysis of the US economy shows that there is some correlation between embodied energy and economic value but it is not an accepted theory. More detailed discussions of the energy theory of value are in Martinez-Alier (1987) Faucheux et al. (1995) and Smil (1992). The analysis in this thesis does not depend an energy theory of value, but uses energy as an indicator of some key factors that affect economy growth.

3 Review of energy-economic models

There has been a proliferation of "energy economy" models since the early seventies. The general aim of these models is to investigate the links between energy and economic activity. A large number of these models are used for economic forecasting using econometric techniques (Werbos, 1990). These models are satisfactory for short term energy demand forecasting but unsatisfactory if there are significant changes in the economy (Lapillonne and Chateau, 1979). Changing the structure of an economy can have a significant influence on the energy demand of the economy. Some analysts have developed dynamic input-output models that adequately account for large changes in the structure of an economy[2] but these are used mainly for energy demand forecasting rather than investigating physical limits of economic growth. A detailed discussion on standard energy-economy models is given by Cofala et al. (1990).

3.1 Energy to GNP ratio

The ratio of energy to GNP is often quoted as an important indicator that shows the quantity of energy required to produce a unit of economic output (Parliamentary Commissioner for the Environment, 1992). This ratio has been falling in the USA since the energy crisis of the early 1970's (Schipper and Meyers, 1992). The conclusion from this is that energy is not essential and we use less if the price is high enough. However, the detailed analysis of Schipper and Meyers shows that: "structural factors are often as important as energy efficiencies in determining the ratio (ibid. p. 55)" Schipper and Meyers estimate that the main reason for the decreasing energy/GNP ratio in the USA was a change in structure. There has been a shift towards products that intrinsically require less energy to produce per unit of value added and many energy intensive products are now imported rather than made in the USA. International energy intensity figures back this up - in the 10 years to 1991 energy intensity fell by 1.3% a year in the rich countries yet it rose by 1.1 % per year in the developing countries (Woodall, 1994).

The structure of an economy is a major determinant of its energy requirements. It is for this reason that the energy/GNP ratio is not necessarily a good indicator of the biophysical efficiency of an economy. An additional complicating factor is the shift from low quality energy to high quality energy (Kaufmann, 1991). Smil (1991) goes as far as to say "energy/GNP ratio misleads as much as it enlightens (Smil, 1991, p. 272)." Similarly, Schipper and Meyers think "the energy/GNP ratio indicator obscures far more that it reveals (Schipper and Meyers, 1992, p. 54)." Economies that produce high-tech value-added goods such as Japan will tend to have a lower energy intensity than economies that produce mainly energy intensive commodities such as pulp and paper, chemicals and metals. Differences in energy/GNP ratio between countries are also significantly affected by climate, recreational habits and geography (Smil, 1992). In New Zealand energy intensive industries are still a significant part of the economy. It does not make sense to compare trends in energy/GNP ratios without understanding the different structures of the economies. An aim of this investigation is to determine to what extent energy is linked to economic growth. It has been noted by Ekins (1993) that decoupling energy and GNP "has occurred to some extent, but the entropy law decrees that it can never be complete (Ekins, 1993, p. 272)."

4 Net Energy

It has long been recognised that in order to make energy accessible, energy needs to be expended. The energy delivered minus the energy expended is the net energy delivered. There are many different forms of this net energy concept. Three of the more common measures are Energy Requirement of Energy (ERE) (Slesser, 1991), Energy Return On Investment (EROI) (Cleveland, 1984 and Hall et al. 1986) and Energy Yield Ratio (EYR) (Odum in: Peet et al., 1987). The difficulty with measurements of net energy is that it is difficult to calculate the total energy requirement of goods or services. One needs to be able to calculate the total embodied energy.

5 Embodied energy

The motivation for energy analysis is to quantify the connection between energy demand and economic development (Brown and Herendeen, 1995). The difficulty is that often the direct energy required to produce a good or service is only a small part of the total demand for energy. The embodied energy is a measure of the total energy required to produce that good or service.

Figure 8-1 illustrates the direct and indirect energy flows for the production of agricultural output in a hypothetical economy. Energy is expended in making the capital structures that produce the agricultural output, and energy is also required to make the capital structures needed to supply fuel energy. A real economy is much more complicated, of course, but much of the detail in a real economy can be captured by data from input-output studies. The static input output methods are briefly explained in Appendix 2.

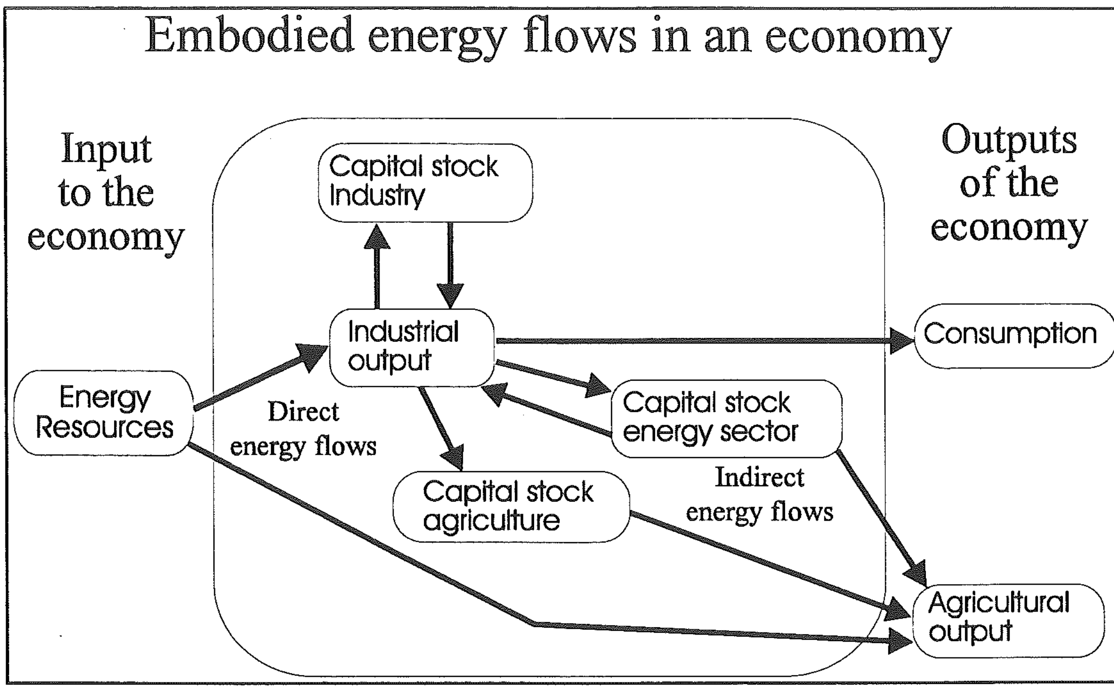

Figure 8-1 *Embodied energy is the total amount of energy that is irrecoverably dissipated to supply a good or service.*

One of the aims of this thesis is to develop a dynamic systems energy analysis model. This will allow for the investigation of a much larger range of scenarios that can include factors such as structural change of the economy, capital stocks and changing efficiencies. Many indirect energy costs of different development scenarios are not obvious, as the results of the dynamic analysis of the New Zealand economy in Chapter 16 show.

5.1 Energy quality and boundary - different types of energy analysis

A common difficulty with energy analysis is deciding how to add the different qualities of energy together and where the system boundary should be drawn. The difficulty of drawing an appropriate boundary is best illustrated by an example. If one wishes to calculate the energy required to produce a bag of potatoes the direct fuel and the indirect fuel required to produce the capital can be easily calculated. Should the solar energy required to produce the potatoes be counted? What about the energy required to feed and house the people who grow and package the potatoes? How far back should the energy analysis go? These types of decisions can only be resolved by judgement decisions (Brown and Herendeen, 1995).

Energy analysis is complicated by the different qualities of fuels available. One GJ of electricity is of a higher quality than one GJ of coal. Many authors have tried to combine energy of different quality into some meaningful index (Cleveland, 1992, Patterson, 1993). Most fuels can be split into two different qualities: one is electricity and the others are hydrocarbon fuels such as oil, coal and gas. Slesser notes that:

> The differences between negentropy and enthalpy of combustion are small, and the error incurred in assuming commercial fuels all enjoy the same quality is certainly smaller than the error in the measurement of economic variables (1990, p. 14)

Deciding which conventions to use in energy analysis will depend on the purposes of analysis. There is no universally correct method and different methods will give different insights. Given the difficulties in resolving issues of boundary and type of energy to include, several different types of energy analysis have evolved. The three common types of energy analysis are; commercial energy analysis, solar energy analysis and fossil energy analysis. The pros and cons of each are briefly discussed below.

5.2 Commercial energy flows

Commercial energy flows (also referred to as "consumer" energy) are defined as commonly traded fuels such as gas, coal, oil, wood and electricity. This is a similar classification to Cleveland's (1992) "economic energy," and Herendeen's (Brown and Herendeen, 1995) "cultural" energy. Typically these energy forms are much more concentrated than direct solar energy. Commercial energy or fuels are in a form that can be used directly within the economy. The commercial energy flows are a measure of the physical difficulty of achieving a task in addition to that naturally provided by the sun.

It is the commercial flows of energy that enable the economy to grow, rather than just solar or fossil flows of energy. Many "less-developed" countries have a huge inflow of solar radiation but are unable to raise their standard of living. Commercial energy amplifies the production possibilities of a purely solar economy (Odum, 1976). There is no doubt, however, that the commercial energy flows would not sustain life for very long if there was no solar flow of energy. If the sun stopped shining, then life on earth would cease to exist in a short time. There is no control over the solar radiation entering the earth, so effort should be concentrated on ways in which useful goods and services can be amplified by technology and commercial flows of energy.

Currently a large proportion (80-90%) of the world's commercial energy comes from non-renewable sources. There is potential for more commercial energy to come from renewable resources. For example, almost 80% of New Zealand's electricity comes from renewable hydro sources. It has yet to be proven, however, whether a modern economy could be run entirely from renewable sources of energy.

Analysis of commercial energy focuses only on human uses of energy and what can be achieved with it. This is the form of energy that is required to maintain economic development and is on most concern to the population. Analysis of commercial energy flows thus gives insights to questions of technological and economic development.

5.3 Solar energy flows

Over the last 20 years Odum (1971, 1976, 1994) has been developing a system for calculating the total energy required to produce a good or service. Odum's energy analysis is different from other methods of energy analysis in that it combines solar energy and other forms of energy. Odum's new unit of analysis is called eMergy

> The eMergy approach seeks to value both those transactions that have money flows associated with them, as well as these other contributions from nature that are not recognised in the usual exchanges involved in the economy (Odum 1994, p. 20)

The methodology focuses on the work done by solar energy that is not usually counted. The other concept that Odum has introduced is Solar Transformity. He defines Solar Transformity as "the solar eMergy required to make one joule of service of product. Its unit is solar emjoules per joule." (Odum, 1994, p. 203) There are several problems with this methodology, among which are measuring environmental services in terms of energy and the assumptions that need to be made when adding energy of different qualities.

The general conclusion drawn from Odum is that, as fossil energy becomes more scarce the production possibilities of the economy will reduce (Odum, 1976). He is not hopeful for the development of solar technologies as they do not yield "net eMergy" according to his analysis. He suggests most technologies require more eMergy than they produce. Because the eMergy analysis method concentrates on solar energy it is best suited for analysing how ecological cycles and the economy interact. This may give insights into how industrial production affects ecological energy flows and the associated feedbacks.

5.4 Depletable energy flows

ECCO (Enhancement of Carrying Capacity Options) is an energy analysis method developed by Slesser to analyse carrying capacity[3]. The methodology assumes economic output is a function of the embodied fossil energy required to produce the goods and services in the economy. Because of possible limits on fossil resources it is thought that an analysis of these resources will show possible physical limits. This form of energy analysis is based on the IFIAS convention (Energy analysis, 1976). Solar flows of energy are indirectly accounted for by limits on land availability. Slesser's approach stresses the importance of dynamic changes in the economy. The feedback structure is designed to calculate the total fossil energy required to produce a good or service.

Analysis of embodied fossil energy gives insights into the role of depletable resources and economic development. For example, one of the aims of the analysis of Slesser is to investigate if there is sufficient time to make the transition away from fossil energy to some new form of energy. The embodied fossil energy information also indicates the total carbon dioxide production of each of the sectors of the economy.

Although the dynamic energy analysis model developed in Part 3 of this thesis is based on the embodied fossil energy of Slesser it can be adapted to use any form of energy analysis. That is, different energy boundaries and methods of adding energy can be included in the model.

6 Criticisms of energy analysis

There have been several criticisms of energy analysis as a tool for providing information to aid policy decisions. The criticisms fall into two groups. The first is from economists, for example Huettner (1976), and the other is from people who have tried to use energy analysis without the desired results (eg Leach, 1975).

The criticisms of Huettner are directed at energy analysts who aim to maximise the net energy of the economy rather than net utility as economists do. As he correctly points out this type of analysis implies an energy theory of value which, as already discussed, is not widely accepted. The focus of his criticism is then on the energy theory of value. The aim of most energy analysts, however, is not to maximise net energy but to investigate energy requirements as a means of analysing physical economic processes. Energy or embodied energy is an indicator of technological progress and long term resource availability.

The criticisms of energy analysis, from Leach (1975), are based on the problems of defining boundaries for energy analysis, determining energy quality and the effect of changing technology. His argument is that there is no "correct way" to add energy together and how to decide which energy to include. As discussed above this requires some form of judgement and hence it is no longer a value free analysis. It is true that there is no universally valid net energy, but as discussed above, each of the different types of energy analysis can give different insights to a particular problem. There does not need to be a specific "correct" form of energy analysis to make it useful.

7 Summary

Energy has been identified as a non-substitutable, non-recyclable essential input to any economic process. This, along with its links to pollution and the large scale of energy projects means energy has special significance in analysing long term economic growth. Energy analysis is an important tool to supplement economic analysis. It does not replace economic analysis with an energy theory of value but it gives a physical analysis which provides different insights. There is no correct form of energy analysis and there is no unique objective ways of defining system boundaries and how to add energies of different qualities.

Different forms of energy analysis have evolved to tackle different questions. Each type of energy analysis gives a different insight to problems. Odum's eMergy analysis appears best for analysing ecological limitations imposed on economic activities. Slesser's embodied fossil energy analysis is better suited for analysing depletable resource flows and carbon dioxide production. The analysis of commercial energy provides insights into how much physical effort is required to achieve a task over and above that already naturally provided by the sun. This form of energy analysis maybe best suited for analysing technological limits and economic development.

Notes

1. Energy can only measure the physical difficulty of achieving a task. There may be all sorts of social difficulties that energy cannot measure.

2. PILOT is a dynamic input-output model with flows in physical units (Dantzig et al. in: Cofala, 1990)

3. This energy analysis method is discussed in more detail in Chapter 12.

Chapter 9: Growth theory, technology and resource availability.

The aim of this chapter is to investigate the different ways in which a physical economy can grow. From this, possible *physical* restrictions to growth can be identified. In particular the roles of technology, resource availability and the fraction of economic output that is invested are investigated. The economic model developed in this chapter has a different philosophy from conventional economic models that aim to predict human behaviour (demand for goods and services) through estimating factors such as prices, elasticities, interest rates, profits etc. These conventional economic models endogenously determine the allocation of capital and labour by attempting to maximising output. Instead of having a model that endogenously determines the allocation of capital and labour growth in the model is determined exogenously. This simplification makes it easier to understand and identify the critical physical factors that allow economic growth to take place. The conclusions from this model are not new to economists but are in a form that makes the key physical determinants of economic growth clear.

1 Economic output and production functions

Most economic growth models are based on variation of the Cobb-Douglas production function (Victor, 1991). These functions are of the following general form[1].

$Q = Ae^{rt}K^{a1} L^{a2}$ 9-1

Where Q is the production, A is a simple scale factor, t is time, r is a parameter whose value must be selected, K is capital and L is labour. The indices a1 and a2 are the shares of income that goes to each factor (a1 + a2 = 1). Many variations on this type of production function have been used (Victor, 1991). There are several difficulties with

Cobb-Douglas production functions. One of the main restrictive assumptions is that technical progress is presumed continuous and constant over time (Benhaim and Schembri, 1994). As explained in the following sections, technical change is a key requirement of economic growth that justifies further investigation. The other difficulty with this type of production function is that it assumes total substitution between production factors is possible. Peter Victor noted:

> In a Cobb-Douglas world, no matter how far an economy goes in substituting capital for resources, the potential for additional substitution never diminishes (Victor, 1991, p. 196).

This implies that no minimum threshold of particular inputs are essential to produce any specified level of economic output[2]. This assumption has been questioned by many authors (Daly, 1991, Constanza, 1991, Peet, 1992) and is discussed further in Chapter 4.

In recognition of the importance of energy in producing goods and services a number of authors have attempted to include energy in the standard Cobb-Douglas production function (Faucheux, 1993). The detailed analysis of Faucheux concluded that:

> Despite the increasing sophistication of production functions with energy inputs, we are still very much lacking in knowledge as to the long term substitutability of energy and capital, the technical progress/linkage, and the ways in which we can take the thermodynamic specificity of energy inputs into account (Faucheux, 1993, p. 52).

The main advantage of the Cobb-Douglas production function is that it is very easy to manipulate analytically. As with other economic production functions it is possible to endogenously find the allocation of capital and labour to maximise the output of the economy. Kaufmann (1995) has used a Cobb-Douglas type model to illustrate the dynamic effects of environmental degradation on economic output. The disadvantage with this type of analysis is that it is difficult to see what specific physical assumptions are required for a given growth scenario.

It should be stressed that the model presented in this chapter does not have a method for endogenously determining substitution between capital, labour and materials based on elasticities such as the models based on Cobb-Douglas production functions. The purpose of the model is to understand the physical assumptions that must lie behind any growth scenario whether it is optimal or not.

1.1 Using an influence diagram as a production function

The "well behaved" Cobb-Douglas type of production function as used in neoclassical economics is not satisfactory for a physical analysis of economic growth. This type of function suggests that the combination of inputs creates outputs. In reality there are dynamic factors that influence the production process, such as the need to process resources into intermediate goods, and delays of capital formation etc. Instead a simple production process can be represented by an influence diagram[3] (Figure 9-1). This is similar to the activity analysis approach of Koopmans (1951) that has been adopted by the neo-Austrian school of economics (Faber et al. 1990, p. 33). It also has similarities to neo-Ricardian production functions (Benhaim and Schembri, 1994).

Figure 9-1 captures the important dynamic influences that create economic output. The "Output" is a function of the capital stock; the other factors of production such as labour resources and energy are accounted for in the ways in which they change the

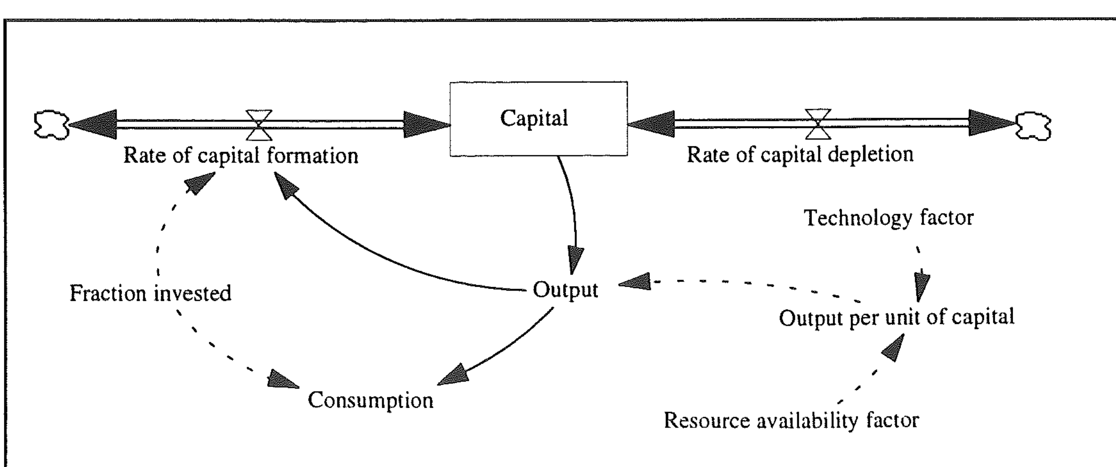

***Figure 9-1** Influence diagram of the important physical influences that affect economic growth.*

"Output per unit of capital." This type of production process representation does not lend itself to maximisation or optimisation of utility but can be used to simulate different scenarios to see what physical assumptions are required to make the scenario materialise. Each scenario will have to make the substitution and technology assumptions explicit rather than having them predetermined by the type of production function used.

2 Simple economic growth model

The diagram in Figure 9-1 shows a simple model of an economy. The model uses standard system dynamic notation[4]. "Capital" is the physical stock of production facilities in the economy. This capital is not money but factories, tools and machines[5]. This "Capital" wears out ("Rate of capital depletion") and is replaced ("Rate of capital formation"). The "Output" of the economy is derived from the "Capital." The "Fraction invested" is the amount of "Output" that is reinvested to maintain or expand the "Capital." The remaining "Output" is available for "Consumption." The "Output per unit capital" determines how much can be produced from a given stock of capital. This ratio can change due to influences from the changing technology and resource availability (see below). Economic growth is based on the positive feedback loop from "Capital" to "Output" to "Rate of capital formation." Economic growth is defined here as growth in the flow of consumption goods and services available to the population per unit of time[6]. The production process representation in Figure 9-1 forms the basis of more complicated production process system diagrams developed in Chapters 10 and 11.

2.1 Fraction invested

Classical economic growth theory, at its simplest, states that some economic activities generate a surplus. Reinvestment of that surplus is the main influence on the rate of economic growth (Eltis, 1984, p. 311). From this one would assume that increasing the fraction invested would increase the rate of growth of industrial output and hence consumption in the long term. That is, if more is saved or invested the quantity of capital will increase and the output that can be made from that capital will increase. However, increasing the fraction invested does not increase output per worker unless there is an increase in worker productivity at the same time. If, for example, more farm machinery is bought but it is used no more "efficiently" the output per worker will remain the same and total output will be determined by the size of the labour force. "Classical" economists usually assumed that there existed a "reserve army of labour" and/or that population growth at least matched output growth. In these model it is possible to increase output by increasing labour but the key interest is the growth input per person so for this discussion it is assumed that population and unemployment are held constant.

If, at the turn of the century, capital accumulation in agriculture consisted of increasing the number of horse drawn tools instead of the shift to mechanised farm machinery then agricultural output per labourer would not have increased. Accumulation of capital in its self will not increase output per unit of labour. By definition labour productivity can only be increased through technological change. Increasing the fraction invested will not cause an increase in economic output per unit of labour unless there is an associated technological improvement[7]. That is, increasing the quantity of capital will not increase the output unless the new capital has better labour productivity. A high fraction invested is a necessary but not sufficient condition to increase economic growth.

The growth models of Solow (1988) emphasise the importance of technology rather than savings (investment) rate as the cause of economic growth:

> The permanent rate of growth of output per unit of labour input is independent of the savings (investment) rate and depends entirely on the rate of technological progress in the broadest sense (Solow, 1988, p. xii).

His models show how growth converges to a "natural growth rate" by optimising the saving rate to maximise a welfare function. This natural growth rate is determined by exogenous technological factors and "....the theory has very little to say about the long-run growth rate itself" (Solow, 1988, p. 77). Even more recent economic growth models such as Romer's endogenous technology model do not give insight into the long run growth of an economy; "unbounded growth is more like an assumption than a result of the model" (Romer, 1990, p. 84). However, economists do recognise the importance of technology and efforts to understand technology in endogenous growth models are increasing.

In conventional economic models the fraction invested is usually endogenously determined by criteria such as maximising profit or maximising welfare. Faber et al. (1990) maximise an intertemporal social welfare function to determine the "optimal" consumption and capital accumulation (they include consumption over two time periods with a positive rate of time preference which recognises the fact[8] that people prefer to consume now rather than in the future). Because only physical possibilities are being investigated in this thesis we are interested in physically possible solutions rather than socially optimal solutions. Socially optimal solutions will be a subset of the physically possible solutions. Exogenously determining the saving rate simplifies the model considerably, clarifying the role of key physical factors that may limit economic growth[9].

2.2 Technology

Perrings has defined technology as "the pool of knowledge that bounds all material transformations of the general system" (Perrings, 1987, p. 49) Thus technology defines the possible methods of producing economic output. "Improving" technology can increase the amount of output from a given set of inputs. This definition of technology includes a broad range of possibilities including changes in the way labour and resources are used. This definition of technology also includes substitution between the factors of production; labour, resources and capital. The role of technology in the economy is more complex than is indicated in Figure 9-1 and this is discussed in detail in the following chapter.

2.3 Resource availability

The following discussion on resource-pollution scarcity only applies for constant technology. The amount of effort required to make resources available to the economy is not constant because resources are not homogeneously distributed. If one assumes a perfect knowledge of the resource base then, in theory, the highest quality resources will be the first to be used. As the highest quality resources are used (eg surface coal) more and more effort will be required to retrieve resources in the future. In this simple model the increased effort will decrease the "output per unit of capital." In this chapter the phrase "diminishing returns" is used when the quantity of output per unit of capital changes. As an example, the first hydro power station will be built where there is a natural valley, large water flow with a large water height difference. The next power station is subject to diminishing returns as it will require more effort per unit of energy delivered. Ricardo's explanation of the decreasing quality of land is another example of decreased resource quality as more of the resource is used.

The quality of resources may not always decrease over time. It is possible that new sources of easily accessible resources will be found, but the general case, in well explored areas, is that resources will become less and less accessible. Boulding (1966) suggests we have moved away from a "cowboy" economy in which there is a vast area to explore to a "full" economy with few new frontiers to be explored.

Pollution can decrease the "output per unit of capital" as well. If there is an undesirable effect resulting from production, that needs to be controlled, then this will increase the effort required to produce a given output. To maintain any given level of environmental quality, production will require more effort as the material throughput of an economy increases. Pollution may also affect the production precess directly if the pollution decreases production, for example pesticide residue may affect agricultural productivity (see Chapter 11).

3 Using this simple model to understand sustainable development.

There are several different cases that can be "tested" using this simple model in Figure

9-1, that clarify the role of technology and resource availability in economic growth. This model applies only to a closed economy (no imports or exports). The arguments for each case can be followed by referring to the simple influence diagram in Figure 9-1.

3.1 Case 1. Constant population, constant output, constant technology, only renewable resources and no pollution.

In this very simple scenario the fraction invested is constant to maintain the capital at existing levels. The quantity of renewable resources used by the economy is also constant so there will be no diminishing returns due to changing resource availability. The renewable resource flow will be able to be used *ad infinitum* and the "Output per unit of capital" will remain constant. So long as the output remains constant the economy is sustainable. If output increases, new renewable resources will be required and these will be subject to diminishing returns. This situation describes the physical economy of many pre-industrial cultures. *We can conclude that an economy with a constant population and constant output that uses only renewable resources does not require technological advancement to sustain economic output at a constant level*[10].

3.2 Case 2: Constant population, constant output, constant technology, using renewable and non-renewable resources.

If some resources used in the economy are from non-renewable sources, they will be subject to diminishing returns. Even for a constant population with constant economic output new resources will be required. Assuming the area is well explored the search for new resources will be subject to diminishing returns. In the absence of technological improvement this will cause a decrease in the "Output per unit capital" which will cause the economic output to fall. Often this will be a very long term argument, as the resource base may be vast with the quality diminishing very slowly. The same arguments can be applied if there is a significant pollution output. *The conclusion from this case is that any economy that uses non-renewable resources requires technological* *improvement just to maintain economic output at a constant level over the long term.*

3.3 Case 3: Increasing population - Constant economic output per person.

The fraction invested can be set so that the capital per person employed remains constant[11]. This fraction invested will need to be higher than for a constant population to enable the capital stock to grow at the same rate as population. The effect of diminishing returns due to non-renewable resources will be stronger in this case as the resources will be used at a faster rate due to an increased number of consumers. There will also be a diminishing returns factor due to renewable resources. This is because more renewable resources will be required. The best quality resources will have been used first meaning that less productive resources must be used to expand the economy. To maintain output per head of population technology must improve at such a rate as to offset the diminishing returns due to renewable and non-renewable resources.

Some economists, for example Simon (1981), see the expanding population as a blessing as it means there are more people to create technical solutions[12]. Other economists such as Dasgupta and Heal recognise the effects of exponentially increasing population *ad infinitum*: "the implication of an exponentially rising population is an absurdity, if only for reasons of space (Dusgupta and Heal, 1979, p. 194)." Hence they hold population constant in their economic growth models.

Increasing population increases the effects of diminishing returns due the higher resources and pollution volumes. *For a growing population to maintain constant economic output per head, continually improving technology is needed to offset the diminishing returns of renewable and non-renewable resources ad infinitum.*

3.4 Case 4. Constant population - Growth in output per person by labour augmenting technology.

If the fraction invested is high enough, the capital available for investment will enable the total stock of capital to grow, which will enable output to grow. Labour productivity is assumed to grow to match the difference between output growth and population growth. For example, if output grows at 3% and working population at 1% then the labour productivity must be increasing at 2%[13]. This means that the economic output per working person can only grow if labour productivity increases. The only way productivity can increase is by changing technology (changing the method of production). So it is intuitively obvious that the only way the output per person can grow is that more output is produced per person (i.e. the economy becomes more capital intensive).

The diminishing return effects due to renewable and non-renewable resources will be increasing at a faster rate then the previous cases due to the increased flow of resources required by the economy. For simplicity we assume that the flow of resources increases at the same rate as output. If this is the case, technology will need to increase at an even faster rate to offset the resulting diminishing returns. *The economic output per person can increase if technology offsets the effects of resource-pollution scarcity and is able to increase labour productivity.*

4 Long term economic growth. Which is dominant, technology or diminishing returns due to resource-pollution scarcity?

Many authors have recognised that economic growth is closely related to technical progress on one hand and resource-pollution scarcity on the other (Faber et al. 1990, Kaufman, 1995). Samuelson and Nordhaus assert that:

> In the race between diminishing returns and advancing technology, technology has won by several lengths (1989, p. 859)."

However, they go on to say that:

> ...there is no theoretical reason why technological innovation should remain high, forever raising living standards and offsetting diminishing returns. The most recent deviant period, since 1973, has witnessed a marked slow down in growth of output, real wages, and output per worker. While it is impossible to say how long this period of diminished macroeconomic performance will persist, we must emphasise that there is no *logical* reason why the future cannot be sharply divergent from the first three quarters of the twentieth century (1989, p. 862).

Analysis of economic growth using Cobb-Douglas type growth equations say nothing about whether technical change can overcome the effects of environmental degradation (Kaufman, 1995, p. 78).

The difference between the "optimists" and the "pessimists" depends on whether they think technology or resource-pollution scarcity will dominate in the future. History would certainly support the conclusion that technology has dominated any effects of diminishing returns since the industrial revolution, but can we understand how this race between technology and diminishing returns will end up in the future? Is there anything that limits the advance of technology? The importance of defining limits on technology has been noted by Solow:

> If real output per unit of resource is effectively bounded - cannot exceed some upper limit of productivity which is in turn not too far from where we are now - then catastrophe is unavoidable. In-between there is a wide range of cases in which the problem is real, interesting, and not foreclosed (Solow, 1974, p. 11).

The relationship between technological advance and diminishing returns is complex, as each can influence the other (Simon, 1981). Trends in technology and diminishing returns are analyzed in the following chapters. The analysis of these trends builds on the basic production structure in Figure 9-1 and uses the concepts of energy analysis and learning curves to build up a picture of how change may occur in the future.

5 Indicator of "weak" sustainability

The simple model developed in this chapter shows that there are fundamental problems with the indicators of "weak" sustainability proposed by Pearce and Atkinson (1993)[14]. According to their theory an economy is sustainable if savings (investments) are higher than the depreciation of natural and human-made capital[15].

$$Z > 0 \quad \text{if} \quad S > (\delta_m + \delta_n), \qquad 9\text{-}2$$

Where Z is a sustainability index, S is savings, δ_m is the value of depreciation on human-made capital, and δ_n is the value of depreciation on natural capital. Equation 9-2 gives the impression that the more that is being saved, the more likely it is that the economy will be sustainable. Yet it mignt intuitively be argured that if more is saved, there will be more human-made capital, and more than likely more production that requires more resources and creates more pollution. All of this will need to be offset by an even faster change in technology which may be the critical limit. In fact, equation 9-2 glosses over key questions of limits to substitutability and technological advances, and just assumes that these are possible. The Pearce-Atkinson indicator represents, in effect, an attempt to infer an economy's sustainability potential into the future on the basis of aggregate economic value measures at one moment in time. But the characteristics of natual resource avialability, sustitutability and so on upon which this inference depends are the key matters needing to be investigated, not things to be presumed. The dynamic model developed in this chapter allows an understanding of the dominant physical factors that may limit long term economic growth.

6 Summary

The dynamic model of economic growth emphasises the two opposing factors influencing economic growth; technological imporvements and diminishing returns due to resource-pollution scarcity. By using this model for different assumptions about population growth, output and resources use the following conclusion can be made.

Diminishing returns due to resources and pollution are increased with increased output. Because a growing population usually increases total economic output, population growth increases the effects of diminishing returns due to resource-pollution scarcity. The diminishing returns decreases the "output per unit of capital" and these decreases must be matched by technological improvement to maintain economic output per head of population. Any increase in economic output per head requires a technological improvement (increasing the fraction invested is not enough by itself) in addition to that required to offset diminishing returns. It can be concluded that to maintain economic growth at a certain percentage rate requires an improvement in technology at an even greater percentage, due to the effects of diminishing returns.

Historically, technological improvement has dominated any diminishing returns caused by resource scarcity and pollution. However, there is no guarantee that this trend will continue forever. The aim of the following two chapters is to analyze these trends to understand how they might change in the future.

Notes

1. These production functions have been extended to include resources and energy separately.

2. In a production function with resources, this assumption means that production may continue when the resource input equals zero.

3. The advantage of a systems simulation model rather than Cobb-Douglas model is more apparent when the model becomes more complicated in the following chapters.

4. The rectangular box in Figure 9-1 represents a stock that has corresponding rates of formation and depletion. The solid arrows represent physical flows. The dotted lines show influences.

5. The numeraire used to measures Capital, Output and Consumption is not important so long as it is a dimensionless index of volume (see chapter 13).

6. The difficulties of defining growth in this way are discussed in the next chapter.

7. There is empirical evidence of a correlation between technological progress and speed of investment (Wolf in: Solow, 1988, p. xxiii). Solow explains this by his embodiment hypothesis; if the speed of investment is fast, then new technology can be implemented more quickly.

8. It may be questioned whether this is a universal "fact" or just true of today's western culture.

9. There is no reason these models could not be adapted later to make the saving rate endogenous.

10. This is a trivial case and it could be called sustainable undevelopment.

11. The fraction of output reinvested can be found using equation S = (K*g+Kd)/O, where S is fraction of output reinvested; K is capital; g is growth rate of population; Kd is capital depletion and O is output (Samuelson and Nordhaus, 1989).

12. The effect of increasing population on technology is discussed further in the following chapter.

13. This is a simple case where technological change is assumed to be purely "labour augmenting".

14. The difference between weak and strong sustainability is defined in Chapter 3

15. The other difficulty with this equation is in assigning a monetary value to natural capital. In addition to this the indicator is not correct unless the natural capital and economic capital are eveluated with proces corresponding to a sustainable development path; and usually the actual market proces will be a long way form these "sustainability shadow proces" (Asheim , 1994).

Chapter 10: Technological change

The important role of technology as a driver of economic growth was emphasised by Schumpeter in the 1930s and has been analysed further by many authors (Ekins, 1994, Solow, 1988, Benhaim and Schembri, 1994, Kemp, 1994, Romer, 1990, Tinbergen and Hueting, 1991). The previous chapter showed how important technology is as a driver of economic growth. Rather than treating technology as an exogenous factor in an economic model the aim is to understand how technological change is linked endogenously with physical trends. This analysis will hopefully give insights about what can be expected from technology in the future.

1 The importance of technology

Assumptions about technological change are critical determinants of the outcome of any long term economic growth model. Ekins notes that: "Everything hinges on the rate of technical progress and possibilities of substitution" (1993, p. 271). The difference between "doomsday" and "endless growth" theories lie in the assumptions made about technology. For example the "footprint" model of Rees et al. (1994) suggests that humans are living beyond their carrying capacity, but this conclusion is reached by assuming no further technological change. Similarly the "Club of Rome" models (Meadows et al. 1972) underestimated the potential change in technology and they have changed this in the latest revision of their model (Meadows et al. 1992). On the other extreme are the models of economists such as Solow (1988), Nordhaus (1974), Simon (1981) and Romer (1990) that assume technological change can and will happen. Under this assumption economic growth will continue *ad infinitum*. Costanza suggests that:

> Given our high level of uncertainty about this issue (technology), it is irrational to bank on technologies' ability to remove resource constraints (Costanza, 1991c, p. 339).

The purpose of the models developed in this Chapter is to analyse the role of technology and its critical driving factors. To make the arguments about technology clear, it is assumed that there are no resource or pollution constraints. These constraints are introduced into the model in Chapter 11.

2 Definition of technological change

Technology has been defined in the previous chapter as a scalar factor that can change the amount of output from a given set of inputs. Some authors split the stages of technology up: for example, Faber et al. (1990) split the stages into invention, innovation and technical progress. For simplicity, all these stages are defined here as technological change[1]. By defining technology as a scalar factor in this model it is assumed that all technology can do is change the output produced from a given set of inputs. There is also the possibility of changing the type of inputs and the type of outputs. A more rigorous definition of technology will use a matrix to define the inputs and outputs of a production process. The models of Perrings (1987) and O'Connor (1993) have defined technology in this rigorous way. A simple definition of technology is, however, adequate to illustrate the points made in this chapter[2].

3 Measurement of technological change

How can technological progress be measured? For example how does one measure the progress made in computing over the last 40 years? The generally accepted way of measuring this is to calculate how the availability has changed relative to human labour. That is, how much computing can be bought with one hour's labour? The real or inflation adjusted cost is a measure of this change in availability. The cost of computing has decreased by several orders of magnitude over the last forty years whereas the costs of housing and transport have not decreased as much. This suggests that technological progress has been faster in computation than in housing and transport.

3.1 End use technology and specific technology

There is an important difference between the end use of a technology and the specific technology. For example the end use of a technology may be to provide heat to a home. There are several specific technologies that can be used to achieve this; electric heaters, gas heaters, wood burners, passive solar heating etc. There has been a significant amount of work done on understanding how different specific technologies substitute for one another to attain the same end use (Ayres, 1985, Marchetti, 1980, Bodger et al. 1988, 1989, 1992). These models usually predict the development of technologies by analysing how market penetration changes. The model of Bodger et al. (1992) show how different energy technologies have replaced each other since the turn of the century. This is an interesting phenomenon but it is not significant for this study. What is of interest in this model is how the real cost changes, of an end use good or service. Changes of specific technologies can be seen as part of the overall technological change. What is important is how the availability or cost of achieving some end use changes over time. The same argument can be applied to services such as communication. It is the cost of sending a given message that is of interest rather than how it has changed for hand delivered letter to telegrams to fibre optics and satellites.

4 Limits on technological change?

If there are physical limits on technological progress then economic growth will be limited. Economic and energy analysis approaches to understanding technological change are discussed below.

4.1 Economic analysis of technological limits

The basic argument behind the unbounded technological progress assumed by many economists is that technology is dependent on human imagination and knowledge and this is unbounded (Simon, 1981, Barnett and Morse, 1963, Romer, 1990). Underlying this is the assumption that all inputs to the production process are characterised by high elasticities of substitution. Any resource can be substituted by labour and capital. Barnett and Morse suggest that technological progress: "is automatic and self-reproductive in modern economies, and obeys a law of increasing returns (1963, p. 42). However, it is generally accepted that the question of technological progress is an empirical question that economic theory cannot resolve (Romer, 1990). Historical evidence suggests that technology has allowed a continued reduction in cost and the economic approach assumes that this long-run trend will continue (Simon, 1981). Simon stresses that it is the long term trend that is important and this has unquestionably been improving. His sole emphasis on long term trends means that if a trend does change he is not likely to notice it for a long time. In essence his assumption is that any current long term trend will continue for ever.

This view of technological progress is not common to all economists. Others, such as Daly (1973, 1980, 1991), Ekins (1994), O'Connor (1993) and Perrings (1987) are not as convinced of the powers of technology to remove resource constraints on economic growth. Typically these economists note the importance of physical flows and how they are bounded by the laws of thermodynamics.

4.2 Energy analysis of technological limits.

The laws of thermodynamics are a vital tool for understanding how technology is likely to advance. We know that there is a thermodynamic minimum amount of energy required to achieve any particular biophysical task in the economy. The energy required for a transformation to occur is a measure of the physical effort involved in the transformation. It gives a physical basis with which to analyse the technological coefficients that allow economic growth to happen. This energy limit on the advance of technology has been recognised by numerous authors (Chapman and Roberts, 1982, Hall et al. 1986). Chapman and Roberts use the standard production function to analyse metal availability. In this case the output is a function of labour, capital and energy. Their analysis found that "the quantities of capital and labour required to produce a metal are expected to show a steady decline with increasing cumulative production." There is no theoretical minimum quantity of labour or capital required to produce metal but the same is not true for energy and in the long term the quantity of energy required will increase. Figure 10-1 shows these long term trends and the effect on the total cost of metal production. However, the long term cost will only increase if the cost of energy increases.

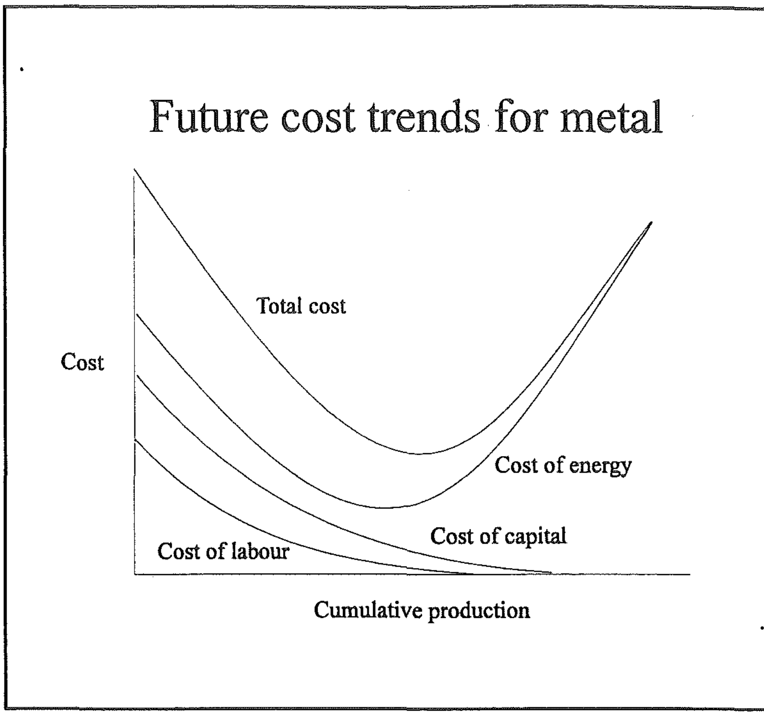

Figure 10-1 *Trend in cost of labour, capital and energy in the production costs of metals. Modified diagram from Chapman and Roberts (1982, p. 153)*

Ruth and Cleveland (1994) have developed a dynamic model that confirms the trends in Figure 10-1 for a number of metals. In the long term the amount of energy required to access a unit of metal will increase. The critical determinant is what is going to happen to the cost of energy in the future. The same type of analysis can be applied to the availability of energy. That is, is may be that the quantity of capital and labour required to produce energy continues to fall while the energy required to produce energy increases. Because of the different possible sources and qualities of energy, it is not possible to define a minimum overall energy requirement for the production of new sources of energy. Given this, it appears that there is no theoretical limit on the cost of energy. For example, it could be possible for one fusion reactor to supply energy for the entire world. This is highly unrealistic in the short term but it is not thermodynamically impossible. The capital and labour requirements for energy may continue to fall meaning that the cost of energy continues to fall. There appears to be no theoretical reason why this cannot happen at such a rate as to off set any increase in energy requirements for resources.

Although there appears to be no strict theoretical limit on technology the slow progress observed in a number of technologies suggests there are some real obstacles to technological change. There is a theoretical reason why increases in energy efficiency cannot continue to improve at a constant rate. There is no such theoretical reason why the capital and labour requirements cannot fall at a constant rate. However, the hypothesis put forward here is that it will be more difficult to decrease the capital and labour requirements (shown up through cost) of tasks that are physically difficult[3]. The thesis here is not that a task with energy limits also has labour and hence cost limits but that it will be harder for cost reductions to continue, for physically difficult tasks.

5 Production process with technology

The following section shows how technology can be included in the dynamic production process representation developed in the previous chapter. Economic output is assumed to be proportional to capital stock as in the model developed in the previous Chapter. It was, however, shown that the critical factor was labour productivity which is determined by the technology of production. Changes in technology are measured by how they change real cost (human-hours/unit) which is the inverse of labour productivity (output/human-hour). Figure 10-2 is a dynamic systems production process for output that emphasises the importance of labour productivity[4].

Output is dependent on labour productivity and the quantity of labour (labour force).

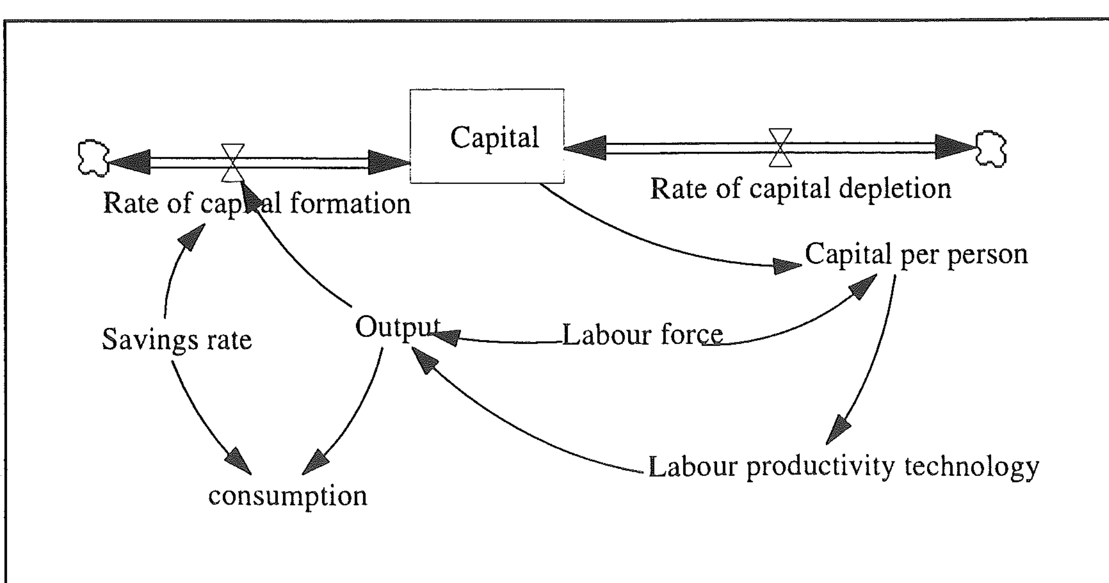

Figure 10-2 *Influence diagram that emphasises the importance of technology (labour productivity)*

In this model changing the saving rate does not change the growth rate of the output but it will increase the capital per person. This process is called "capital deepening" (see previous Chapter). As there is more capital available per person then labour productivity is likely to increase. Capital deepening is seen as a method of increasing productivity but it is the technological change that results from more capital that improves productivity rather than the increased quantity of capital of itself. To understand physical economic growth we need to know what are the critical factors that change labour productivity.

6 Learning curves and labour productivity.

There is a significant amount of empirical evidence to support the idea of a learning curve (Arrow, 1962, Ayres, 1985, Roberts and Chapman, 1983, Kemp, 1994, Sahal, 1975). This learning curve or experience curve shows that the more something is done then the easier it is to do it. More ways to reduce cost are learned, the more something is done. The cost reduction is a function of the cumulative production[5]. The learning curve may be described by the following function[6]:

$$C=C_o*N^{-b} \qquad 10.1$$

C = Cost per unit (or labour input per unit of output)

N = Cumulative production

b = learning index or cost elasticity

$a = 1-2^{-b}$ is the cost reduction for doubling of production

In a typical learning curve, cost per unit falls with increasing production. The most common type of learning curve is loglinear - a plot of the logarithm of the cost versus the logarithm of the cumulative production is a straight line (Kemp, 1994). This means that the learning index is constant.

Equation 10.1 can be changed to represent labour productivity instead of cost[7].

$$LP = LP_0 * N^b \qquad 10.2$$

LP = Labour productivity (output per unit of labour input)

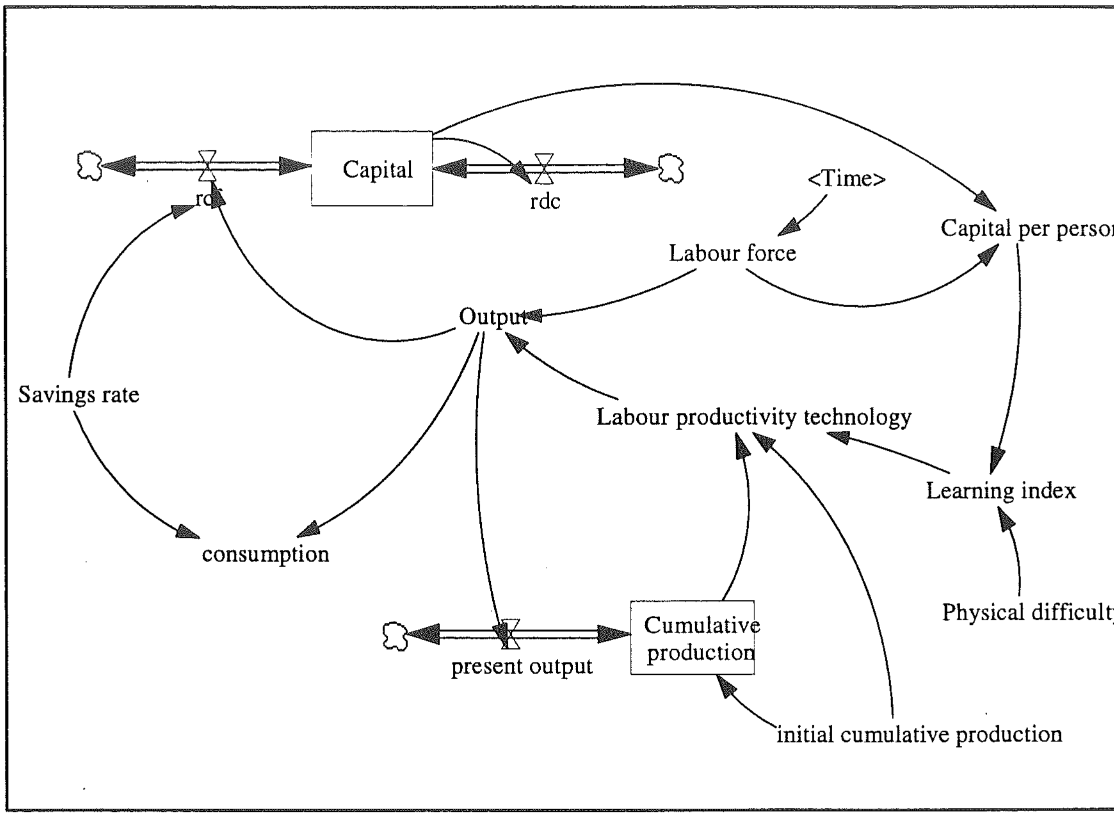

***Figure 10-3** Influence diagram that includes the concept of learning index*

Figure 10-3 illustrates how the learning curve concept can be included in a dynamic production process representation. The cumulative production will change the labour productivity according to equation 12.2. The learning index is now the critical determinant of growth in this model. It is assumed that this is influenced by the quantity of capital available per person and the physical difficulty of the task. The relationships between the capital per person, physical difficulty, cumulative production are essentially empirical. The physical difficulty of a task will suggest a rough range for which technology may progress in a given sector. This may be found from historical evidence. The amount of capital per person is affected by the savings rate, i.e., the more saved the more capital there will be. In this case the increased capital can change the rate of learning, i.e., increase the learning index. The learning index is bounded by the physical difficulty of the task. This model is preferable to one in which the savings rate directly determines the growth of the model as it makes technological assumptions explicit.

Unprecedented technological changes can be easily identified rather than hidden in the model. Historical information on learning rates for different sectors of the economy may also give information on how the technology is likely to change in the future.

Several interesting results come from this simple model. If the learning index is constant then the rate of population growth determines the rate of economic growth. If the population is constant and the learning index is constant the economy can grow forever but the annual growth rate will be continually falling. This is because it takes longer for cumulative production to increase thus learning is relatively slow[8]. Figure 10-4 illustrates how the rate of growth of economic output falls if the population and learning index are constant.

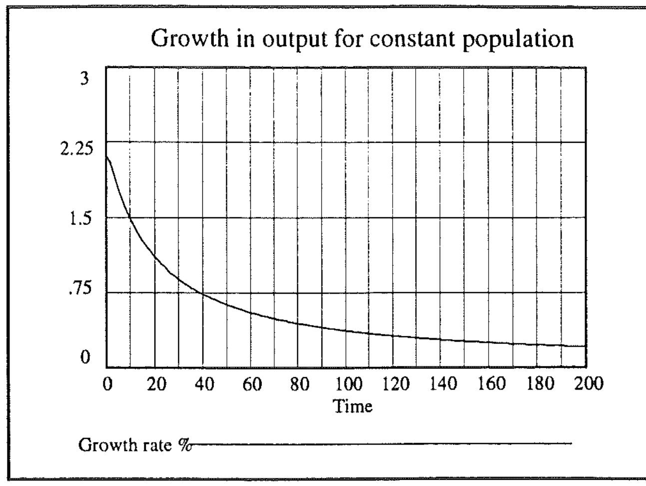

Figure 10-4 *Growth in output for a constant population with a constant learning index that is proportional to cumulative production*

If the working population is growing at a constant rate (ie. exponentially) the growth rate of output can be constant. This is because labour productivity is dependent on cumulative production. If population increases, cumulative production will grow faster allowing faster learning[9]. For a given learning index and population growth the rate of growth of output will converge to some fixed growth rate per year[10]. Figure 10-5 shows that both the growth of output and the growth of output per person grow at a constant rate if the

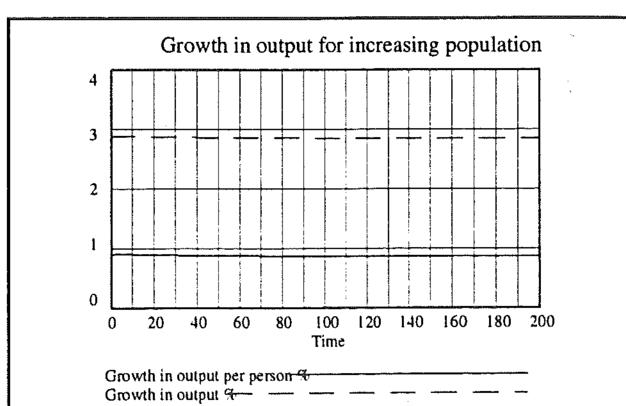

Figure 10-5 *Percentage growth in output for an increasing population.*

population growth rate and learning index are constant.

This model of technological change shows that even when there are no diminishing returns due to pollution or resource scarcity the rate of growth of output per person falls if population is constant[11]. The conclusion from this is not that we should maintain population growth to maintain growth in output per person. The conclusion is that the quantity of economic output may not grow at a constant rate in the future if the rate of population growth declines[12]. Another possibility, however, is that the learning index will increase over time to allow a constant rate of growth for a stable population. Learning may be a function of the time elapsed rather than cumulative production.

6.1 What determines learning index?

Table 10-1 shows there are large differences in the learning index values of different activities[13]. The larger b is, the faster the cost reduction (i.e. faster learning). Technologies with the fastest learning rates tend to be in the electronics industry while

Type of Industry	Learning index (b)
Semi-conductors (1964-77) \$/unit	0.73
MOS dynamic RAM (1973-78) \$/kilobit	0.56
Integrated circuits (1964-72) \$/unit	0.47
Digital Watches (1975-78) \$/unit	0.44
PVC price (1946-1968) \$/lb	0.36
Petroleum refining (1860-62) manhrs/bbl	0.25
Model "T" Ford (1910-26) \$/unit	0.22
Catalytic cracking (1946-58) manhrs/bbl	0.16
Electricity generation (1910-55) \$/KWh	0.075

Table 10-1. Some values of learning index taken from Ayres (1985, p. 379)

the slower learning industries are more physically difficult. As explained in chapter 8 the physical difficulty of a task can be measured by embodied energy required to produce it. The hypothesis here is that there is a relationship between the learning index and the physical difficulty of the task. The physical difficulty is measured by the embodied energy per dollar of goods produced. Unfortunately there are no embodied energy per dollar of output figures for the data in table 10-1 but there appears to be a relationship between learning index and energy intensity.

The reason it is harder to learn to do physically difficult things is that there are physical laws of thermodynamics that impose binding limits. There is a theoretical minimum amount of energy required to achieve any physical task. Although there is no equivalent theoretical minimum amount to labour and capital required to achieve a task, empirical evidence suggests that it is harder to continually reduce the labour and capital inputs for physically difficult tasks. Where there are no physical restrictions it is easier to learn how to do things.

A possible reason for the increased rate of technological progress in some areas over another is that progress is always faster in new areas than in old. For example automotive technology has a much longer history than computing so computing is on the steep part of the learning curve. A comparison can be made between computing and space travel as they both started at about the same time. Space travel has significant physical restrictions and computing does not, hence computing progressed faster than the space travel.

6.2 Alternative measure of the rate of technical progress

A simpler measure of the rate of technical progress is the average yearly percentage decrease in cost of products from different sectors of the economy. In this formulation the progress is assumed to be a function of the time elapsed rather than the cumulative production. The producers' prices index measures the relative change in price of each production sector in the economy. Consistent sets of data for this in the New Zealand economy go back to 1977. The producers price index can be converted into constant dollars using the consumer price index. From this, the real price change over 17 years can be estimated. It is then an easy step to calculated the average yearly change in price. A problem with this sort of data is that there are many nonphysical non-technological factors that affect prices. Examples of these include deregulation of markets, changes in imports tariffs, taxes etc. Ideally one would like less aggregated sectors to test the hypothesis and over a longer time period so the short term fluctuations were not so significant.

When learning average cost reduction per year (learning index) is compared to the embodied energy in different 18 sectors in the New Zealand economy it shows there is no significant relationship. However, less aggregated data over a much longer time period may give better insights about the relationship. Some sectors in the economy that will not be affected greatly by physical criteria such as energy include insurance, government and banking etc. The data needs much more analysis before sensible conclusions can be drawn about the link between energy and technological progress.

6.3 How the learning index changes over time.

A method of testing for technology limits is to measure the learning index and how it changes over time. If the learning index is falling then this will indicate a possible limit on technology. If it is falling it means that the rate of technological progress is decreasing over time. Conversely, an increasing learning index will indicate that technology is self reinforcing as Barnett and Morse (1963) suggest.

6.4 Different types of learning curve

Each sector of the economy may achieve technological change in different ways. For example, some sectors may improve as a function of time while others may improve as a function of cumulative production. Some sector may have constant learning rates while others may be increasing or decreasing. Sectors with similar technological development trajectories are likely to have similar physical characteristics. Technological limits in the agriculture sector are likely to be different to those in services and industry sectors. It is beyond the scope of this investigation to pursue these ideas further but it is perhaps the most interesting avenue for further research.

7 Economic analysis of technology

Most economic growth models include technology as an exogenous input (Solow, 1988). Some attempts have been made to make the concept of technology endogenous (Romer, 1990)[14]. Romer suggests that technological change arises from intentional decisions by profit-maximizing agents. He suggests that it is purposeful intentional actions of people responding to market incentives that create technological change and hence economic growth. Romer does not accept Arrow's (1962) learning curve theory because this assumes the learning is exogenous and independent of the purposeful actions of firms to invest in research. However, both Arrow and Romer miss the importance of physical restrictions on technological change. For example, it does not matter how much more investment goes into transportation, progress in computing will always be more rapid. Their models cannot explain why technological change is faster in some areas than in others as their models do not recognise that technological progress is influenced by factors external to their models such as physical flows. The model in Figure 10-3 recognises that investment can change the rate of technological progress through capital deepening (increasing the capital per person[15]). The additional feature of the model in Figure 10-4 is that physical criteria that affect technological progress can also be included. That is, the physical difficulty of a task can affect the learning index of a particular sector.

Martinez Alier stresses the importance of further analysing technology:

> Economists should also become students of the history of science and technology, since economic agents will take their beliefs about technical change from this history (from where else?). If economic agents believe, for example, that "soon there will be new sources of energy," a belief which will have an effect on the whole pattern of transactions and prices, the economists ought to be under the obligation of studying the social roots of this belief (1987, p.160).

The model developed in this chapter allows physical critera to be included in an economic growth model while still recognising the important role investment has in bringing about technological progress

8 Evidence to support the importance of technology in economic development

Figure 10-6 shows the average GNP per person plotted against the average growth rate over the last 20 years. The countries with the highest growth rates, China and South East Asia, are those with low GNP per capita. That is, they are going from low technology economies to high technology economies. The countries with already high GNP per capita, such as Japan, USA and Europe, are growing at a slower rate as they cannot import already developed technologies to the same extent. Countries with the high GNP per capita will not be growing at the highest rate. There has been a noticeable slow down in the rate of growth of the Japanese economy in recent years. This is not because of lack of savings but because of lack of opportunities to significantly improve technologies.

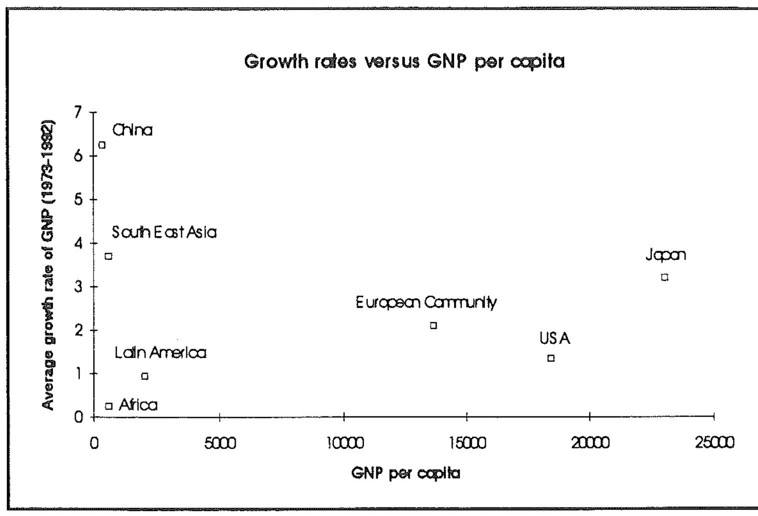

Figure 10-6 Economic growth rates and GNP per capita in the world economy.

There are a significant number of countries, notably in Africa and Latin America, with low GNP per capita and low economic growth rates There are other factors which

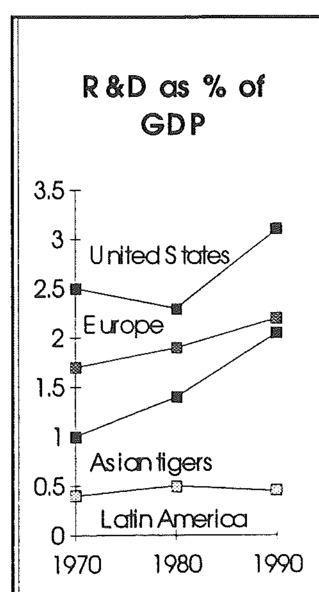

Figure 10-7 R&D spending in the world

prevent the development of these economies that cannot be explained by this physical economic growth theory.

An indicator of the effort required to improve technology is the percentage of GNP spent on research and development[16]. Data from the Economist suggests that this has been increasing significantly over the last 20 years. Two interesting conclusions can be found from the graph is in Figure 10-7. The first is that higher rates of investment in R&D are found in countries with a high GDP. The second conclusion is that the investment in technology via research and development is increasing. This may show some evidence technological limits may be approached. Higher investment is required to achieve a smaller growth rate than in the past.

9 Summary

The model developed in this chapter suggests that it is a nonsensical question to ask: is there going to be economic growth? Rather this type of models show what we intuitively suspect - if there is going to be "growth" it is likely to occur in less physically intensive sectors. People in the future may have better access to information, communication and entertainment services but they seem unlikely to have larger homes and more cars. This is an important distinction. To lump it all together and call it growth in GDP has very little meaning.

From this type of analysis the ways in which different technologies change can be estimated. Not all technology will be influenced in the same way. For example the advance of some technologies may be related to cumulative production while others are related to time and capital deepening. If this is projected into the future then different technological possibilities may be able to be estimated.

Growth modellers have yet to recognise the difference between physical and nonphysical economic processes and the technological differences between them. The value of this analysis is not necessarily that it shows something new but that it develops a theory and a means of quantifying something that we intuitively suspect. That is, that some technologies are easier to make progress on than others.

Notes

1. Where ever possible the phrase 'technological change' is used rather than 'technological progress' as this has connotations of being good when this may not be the case (Jacques and Schembri, 1994)

2. When referring to changing technology it is assumed that it can also mean changing the types of inputs and outputs.

3. As indicated in Chapter 7 physical difficulty can be measured by embodied energy.

4. Output is no longer directly linked to the quantity of capital as it is in classical economic growth theory. Output is dependent on the technology (labour productivity) of that capital. Increasing capital will increase the capital per person which is likely to increase the labour productivity of the capital.

5. It is not certain whether learning is a function of cumulative production or of time elapsed. The most common form of learning curve in the literature uses cumulative production (Sahal, 1975)

6. Taken from Robert U. Ayres (1985). Also see Kemp (1994)

7. Alternatively it can be written:
$LP = LP_o*(N^b/N_o^b)$ where
LP_o= Initial labour productivity
N_o= Initial cumulative production

8. The rate of growth will not fall if learning is proportional to time elapsed rather than cumulative production.

9. This simple analysis assumes that with the increase in population the new labour is of equal skills and that capital is available to enable them to be productive. So if there is a lack of learning due to lack of capital and education, increasing population will not necessarily increase the output.

10. The initial cumulative production determines whether the initial growth rate is high or low. If the initial cumulative production is low, the initial rate of growth will be high and vice versa.

11. The percentage of the population that is working is important. As the population growth rate decreases there will be a smaller fraction working until the population is stable.

12. It is generally agreed that world wide population growth can not continue for ever.

13. These figures are estimated from a graph in Ayres (1985, p.379).

14. Romer's model is not used for investigating the possibility of growth but to explain how technological change develops, "unbounded growth is more like an assumption than a result of the model (Romer, 1990, p. 84)."

15. Note that this extra investment does not have to be machines and factories but can be in institutions to accelerate the learning of the labour force (eg universities etc.).

16. Data from Woodall (1994).

Chapter 11: Resource availability and pollution

This chapter outlines the dynamic process involved in supplying resources to the economy and how this may affect economic growth. As identified in Chapter 6 there are three significantly different types of resources: Recyclable, renewable and depletable. Each of these resources is analysed separately due to its different physical properties. The first section of this chapter shows how possible resource limits can be included in the dynamic model developed in previous chapters. This is followed by a more detailed model of each of the different resources. Much work has been done on how resource availability changes over time. Rather than duplicate this, it has been referred to and shown how it can be included in a dynamic model. The return of resources back to the environment and the potential for pollution are also analysed.

1 Dynamic model including resources.

The dynamic models of the economy developed in the previous chapters do not include resources and pollution flows. Figure 11-1 illustrates how these flows may be included in this type of model. The "Output" of the economy will influence the quantity and quality of resources required and pollution output of an economy. From these flows the capital and labour required to access the resources and control pollution can be estimated. The capital requirements will be determined by the cumulative production and technologies used. Any capital and labour requirements in the resource and pollution control sector will reduce the quantity of capital and labour available for the rest of the economy. If they get too large then they will draw capital and labour away from the main economy which will reduce the available output. This will in turn reduce either consumption or the rate of capital formation. Two indicators of sustainable development will be the percentage of energy and the percentage of capital required to supply resources and control pollution. This gives an indication of the size of

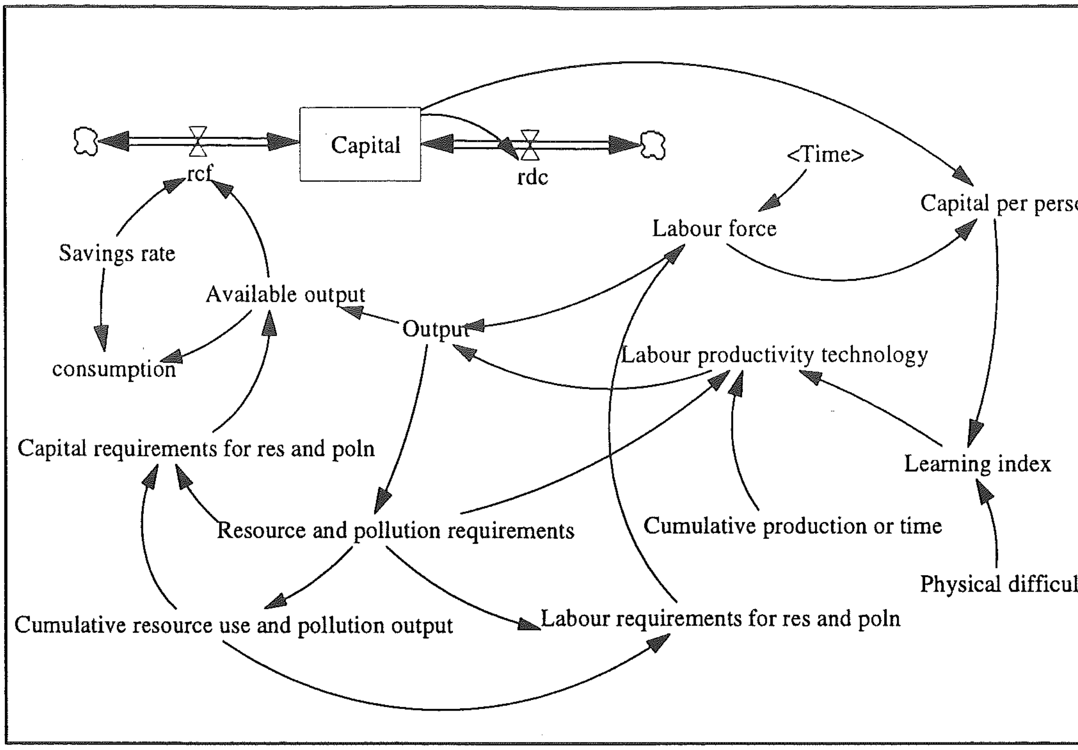

Figure 11-1 *Dynamic model including pollution and resource restrictions.*

environmental services within the economy[1]. The resource and pollution control requirements influence the cumulative resource and pollution output which in turn affects the quantity of labour and capital required to access resources and control pollution. The other important influence is how the pollution output can reduce the productivity of other sectors in the economy. The dynamics of each resource transformation system and the pollution control system are more complicated than the simple influence diagram in Figure 11-1 so separate dynamic models of each sector need to be developed.

2 Energy technologies

As outlined in Chapter 7 energy is a critical resource because its availability can influence the availability of all other resources. Hence, it is discussed separately from the other resources used in the economy.

2.1 Past predictions on energy futures

Predicting future energy technologies is notoriously difficult. Since Jevons first raised the coal question, analysts have been predicting that we will run out of energy resources. The opposite view was expressed by Kahn et al. (1976) who considered that energy costs as a whole are very likely to continue their downward trend indefinitely. This is based on the expectations about new technologies - in this case fusion energy. Kahn stated that:

> The consensus among scientists today is that the commercial feasibility of one of the magnetic fusion systems... is likely to be established by the early 1990's (Kahn, 1976, p. 121).

Similar optimistic views on fusion and breeder fission can be found in the literature of the time (Kavanagh, 1979, Nordhaus, 1974). These statements highlight the difficulty of predicting new technologies.

The technological optimism of the seventies has been replaced by predictions that the cost of energy will increase in the future. For example, Chapman and Roberts suggest: "...fuel prices are likely to increase, in real terms price, by 2-3% per annum for the next 30-50 years (1983, p. 152)." The Economist magazine predicts that: "By the end of the decade we are likely to see substantial price increases, for which the consuming countries,.... are unprepared (Carr, 1994.)." This is important because the scarcity of other resources depends on the availability of energy. The model developed here is not able to predict the price of energy in the future but it can simulate the structural changes based on the capital, labour and energy requirements for the implementation of any new proposal (see Chapter 16).

2.2 Simulation as a method of testing energy futures.

The model developed in this thesis cannot predict what types of energy technology will be introduced in the future. However, the model can test different options to see how they might affect the rest of the economy. The new scenario needs to specify the physical requirements (capital, labour, energy) of a new energy technology. These requirements can be fed back into the rest of the economy so they are dynamically balanced.

2.3 Energy technology in the next 60 years.

Some authors hope or expect a new, as yet unconceived energy technology to be available in the next 60 years (Simon, 1981). If one considers the energy technologies currently used commercially and the origin of their conception it seems unlikely that such a new technology would be commercially available so soon. Almost all currently used energy production technologies were conceived more than one hundred years ago. Even nuclear technologies that have yet to be perfected were conceived over 60 years ago. This suggests that there is a significant gap between the conception and the commercial viability of radically different methods of energy production. Over the last 60 years there have been a vast number of incremental improvements to old energy production technologies. An example of this is the advance of the heat engine from initial steam engines to steam turbines to gas turbines to combined cycles. These gradual improvements will continue and probably could be estimated using the learning curve theory. A brief summary of the possibilities in three areas of energy are discussed below.

2.3.1 Fossil fuel resources

It seems likely that restrictions on the use of fossil energy resources will arise due to pollution rather than depletion. If significant risk is found with the enhanced green house effect then limits on carbon emissions may be possible. Less emphasis is now placed on the depletion of fossil resources than in the debates of the 1970s (Ekins, 1993).

A traditional method of estimating the amount of time before a resource is depleted is to estimate the known reserves, and to compare this to the yearly use of a resource.

This method is very inaccurate as there are always more reserves than is economically worth knowing about. The rate of change of resource use greatly affects the resources to reserves ratio[2]. For these reasons the reserves-use rate method is not used in this model. Instead of using the Malthusian idea of a diminishing stock, the Ricardian concept of diminishing returns is used. The depletion of fossil resources is a function of the cumulative use of the resources. The more that is used the more capital, labour and energy will be required to retrieve them.

2.3.2 Nuclear alternatives

The faith placed on nuclear technology as a means of substituting for fossil resources appears to be less now than 20 years ago. The main problems are involved with the safety, security and waste produced from these plants. As early as 1947 Soddy recognised "the virtual impossibility of preventing the use of the non-fission products ... such as plutonium, for war purposes (in: Martinez Alier, 1987, p. 141)." Countries must pass a political stability test before they are allowed to develop nuclear power stations[3]. Interest in nuclear technologies has fallen off significantly since the Chernobyl accident. However, nuclear energy will continue to be a significant contributor to the economies of those countries already using it but it is unlikely to expand significantly or be adopted by other countries if the present trends continue.

2.3.3 Renewable energy resources

The option for a sustainable future rests on the development of solar technologies to supply the energy required by economies. The sun supplies about 10,000 times the amount of commercial energy used in the world economy (Read, 1994, p. 29). Given this, it would appear to be an easy proposition to convert a small percentage of this into commercial energy to supply a growing economy. However, many authors (King and Slesser, 1992, Odum and Odum, 1976, Pimentel et al. 1994) question the ability of technology to produce energy from the sun in this quantity at an acceptable price. It is difficult to know which renewable technologies are likely to be prominent in the future. The aim of the model developed here is to be able to simulate the introduction of a number of different proposals to see the effects on the rest of the economy. As illustrated in Chapter 16 the introduction of a new technology can have significant effects on the structure of the economy.

The most common method of comparing new renewable technologies is still to measure only the direct costs of the proposals. One has to be extra careful when comparing costs of renewables to fossil technologies because of the intermittent nature of solar energy. It is not always possible to make a direct comparison between the cost energy production from different sources - for example the cost of electricity production from wind or fossil fuels. The reason for this is that it is possible to match the supply to the demand with a fossil fuel source but not with the wind. An added expense for solar technologies is the need for some sort of storage mechanism to be included in the system. In New Zealand the ideal source for this is the hydro lakes. Other alternatives could include having a fleet of electric vehicles that could dampen some variability out of the demand for energy.

In New Zealand it seems very possible to achieve a totally renewable electricity system. New Zealand already supplies 70-80% of its electricity from renewable hydro sources. There is also significant potential for the introduction of wind farms and biomass fuel[4]. However, the largest difficulty is producing transportation fuels from renewable resources. Some alternatives include methanol from wood, methane from biogas, hydrogen from photovoltaic electrolysis of water, and other forms of biomass. Although many of these technologies are proven on a small scale the logistics and dynamics of large scale introduction of these technologies are largely unknown. Renewable technologies may use significant quantities of land. Pimentel et al. (1994) estimate that 40% of current energy consumption in the US could be developed from solar energy technologies, but would require about 20% of total US land area.

2.3.4 Energy efficiency

Improving energy efficiency is a method of increasing the sustainability of an economy. The dynamic models developed in this thesis are ideal for analysing the effects of introducing such technologies. These energy efficient technologies usually require the replacement or modification of capital. The effects of this on the flow of capital and energy demands are included in the model. There are several reports on the trends in efficiency and how this is likely to proceed in the future based of thermodynamic limits on efficiency which can form the basis for data in the simulation model (eg Schipper and Meyers, 1992).

3 Recyclable resources

Chapter 7 defines recyclable resources to include all non-energy materials that are not renewable. Many studies have investigated how the scarcity of these resources change over time. Most studies involve the use of prices as a measure of scarcity. As outlined in Chapter 4 the problem with this is that it does not make the underlying physical and technological causes of scarcity explicit. Norgaard and Liu (1986) emphasize this point:

> Scant attention is paid to the measurement of specific variables (resources quality, technology) that determine the indicated (price, cost) that are used to deduce scarcity (Norgaard and Liu in: Cleveland, 1993, p. 128).

An analysis of these physical and technological forces can be found in studies by Hall et al. (1986), Cleveland (1991, 1993) and Chapman and Roberts (1982). These authors use energy as a measure of the physical difficulty of reaching a resource. Their analyses suggests that there are minimum energy requirements for retrieving resources and that eventually the energy cost of accessing these resources will increase. This will not necessarily mean an increase in cost of the material, as the cost of energy may be declining to offset the increased energy input. It is the availability of energy that determines to some extent the availability of other resources. It is for this reason that most of the effort in this model is on the energy sector.

3.1 Dynamic model of resource availability

For the same reasons as described above the Malthusian stock-supply model is not satisfactory for explaining long term resource availability. Instead the Ricardian concept of declining quality is used. Resource optimists such as Nordhaus accept that higher consumption levels in the future will lead to mining of lower and lower grade ores (1974, p. 24). Whether this leads to continuing decline of the resource/labour price ratio depends on whether technological progress continuous to outstrip the movement to lower grade ores. The quantity of materials to be mined is determined by the activities of the rest of the economy. The labour, capital and energy requirements can be estimated from this. The learning curve concept can be used to determine how technology may change, while the resource availability factor is determined by the cumulative production of the resource[5].

3.2 Future availability of recyclable resources.

Even using price as an indicator of resources availability shows that resources availability may no longer be improving. Fisher concludes that:

> We may be approaching a turning point (indeed, we may have reached it) at which the resource base, after having effectively expanded for many decades, will begin to shrink (Fisher, 1981 p. 126).

Similarly, Slade (1982) showed that the real cost of a number of metals was no longer decreasing and that the prices tended to better fit a U shaped curve.

4 Renewable (ecosystem) resources

Renewable (ecosystem) resources are defined here as all those resources required to sustain life including air, water, food, stable climate. These resources are renewable but potentially depletable (see Chapter 7). Even though these resources are self renewing they potentially impose limits on the growth of the economy. The total quantity of these resources is limited by the size of the earth and our ability to replicate them even on a small scale for sustained periods is questionable[6]. There is evidence that the renewability of these resources is affected by industrial activity. For example climatic stability may be affected by carbon dioxide emissions. It is extraordinarily complicated to define the acceptable pollution limits and limits on sustainable harvest (Ehrlich, 1994). However, none of these limits are significant if one assumes that renewable resources can be substituted with other resources and human made capital. Hence, the degree of substitutability is a central focus for the debates about sustainability. The model developed here cannot resolve this issue as it is largely a question for ecologists. However, the model can test the effect of different assumptions about substitutability.

4.1 Substitutability of renewable resources.

In the very long term the only way to know for sure if human-made capital is substitutable by natural capital is to experiment. The results may not be desirable. Pearce and Turner suggest that: "the presence of uncertainty and irreversibility together should make us more circumspect about giving up natural capital (Pearce and Turner, 1990, p. 51)." The Precautionary Principle is one of the key policies for achieving sustainable development (Costanza, 1994). A large number of other authors stress the non-substitutability of these ecological resources (Daly, 1973, 1980; Ehrlich, 1989; Peet, 1992; Faucheux et al. 1994)

5 Pollution

Pollution feedback can affect economic performance in two different ways. Firstly it may reduce the amount of output that can be produced from a given set of inputs. An example of this would be the effect of soil degradation on agricultural production. The other way pollution affects the economy is that it may require effort in the form of capital, labour, materials and energy to reduce it and thus it reduces the resources available in other sectors in the economy.

Historically local pollution has been a common problem. However, it is only recently that human activities have been large enough to cause pollution on a global scale. The literature on the global pollution problem is vast and beyond the scope of this investigation to adequately summarise. Ekins (1993) has noted the change in opinion about global pollution and its effect on economic limits since the seventies:

> Then environmental limits were perceived to be either nonexistent of automatically self-delimiting. Now the consensus among the mainstream optimists...is that environmental problems are real and threatening and that to be reconciled with continuing economic expansion *active policy* on the part of both business and government will be required (Ekins, 1993, p. 277).

5.1 Uncertainties with pollution

Predicting what might happen to renewable resources because of pollution is an ecological question that cannot be accurately answered (Ehrlich, 1989, Odum and Odum, 1976). Because the response of the environment to pollution is not certain, deciding what risks should be taken is a very important ethical question (see Chapter 5).

Estimation of the effects of pollution on life support systems is difficult because of synergetic effects, thresholds and delayed reactions (Dietz et al. 1992). Synergetic effects refer to the combined effects of a number of pollutants; it is often extremely hard to identify an exact cause and effect when there are multiple causes. Examples of this are the various effects all the different greenhouse gases may have. Thresholds of pollution emission may also be difficult to detect. Small amounts of pollution may have only a small effect until a level is reached which may cause total collapse of the system. An example of this is the "Forest Death" in Europe. Delayed reactions inevitably cause instability when trying to control systems. A potential problem with delayed feedbacks is that cause and effect may be identified too late to change the outcome. There may be potentially disastrous feedbacks that we have not yet conceived. The combined problem of threshold, delays and synergetic effects make analysis of pollution feedbacks almost impossible.

The complexity of estimating how pollution affects different parts of the biosphere is noted by Ehrlich:

> It's a sad fact of life that ecologists have not yet unravelled the mysteries of ecosystems to the point where the long term consequences of most human interventions can be predicted with any degree of precision (1981, p. 12).

Because of the inherent uncertainties involved with pollution it is extremely difficult to control. Environmentalist David Orr describes the process of managing planet earth as: "more akin to child-proofing a day-care centre than to piloting spaceship earth. (Scientific American, 1989)."

5.2 Methods to control pollution

The complexity of controlling pollution is amplified when there are different pollutants causing different outcomes. An example of this is atmospheric warming due to carbon dioxide emissions combined with atmospheric cooling due to particulates. Historical records show that there has been no significant temperature rise in many populated areas in the northern hemisphere. The reason for this is that particulate matter[7] in the atmosphere causes an increase in the reflection of solar radiation which causes localised cooling (Pearce, 1994). The combination of these two effects is to keep the temperature about the same. This is not necessarily a good method of controlling the effects of pollution. It is analogous to controlling the speed of a car not by removing your foot from the accelerator but by applying the brake at the same time. This is inherently unstable.

Technology is often touted as a solution to any environmental problems (Simon, 1981). As an example, Wong (in: Mestel, 1994) proposed a method for reducing the reactivity of CFCs by supplying a negative electric charge to the stratosphere. However, it has since been calculated that this solution would require 30 times the total energy generation capacity of the US. Another example is the proposed space station to reflect solar radiation to prevent global warming (Mantner, 1993).

It is not easy to measure pollution in a rigorous way due to the different type of pollution and the uncertainties of their effects. Some authors, such as Daly (1980), emphasise that minimising throughput of materials is the best way to reduce the effects of pollution. Other authors, such as O'Connor (1993), stress that it is also the qualitative changes to the types of pollution that are important. In the model used here both the material and energy flows are measured so the associated pollution can be estimated. The acceptable level of pollution has to be decided outside the model and included as a scenario variable. An example of this would be to say that the acceptable level of carbon dioxide is x tonnes per year. This method of using exogenously determined emission abatements policies to determine the quantity of capital and labour required to meet them has been used by other modellers (Faber et al. 1990). A number of different technologies for controlling or reducing pollution can then be tested to see what effects they have on the rest of the economy. The preference between prevention of pollution or amelioration depends on the reversibility of the process. As noted by Read: "If taking pollution out of the environment is easier than not putting it in, then that is the thing to do (1994, p. 153).

Notes

1. Environmental services include energy, recyclable and renewable resource transformation systems as well as pollution control systems (see Chapter 7).

2. Many authors point to the failure of this method due the discovery of more resources (Barnett and Morse, 1963, Simon, 1981)

3. Restricted access to nuclear technologies in the Middle East and North Korea are examples of this.

4. Examples of this include production of biogas and new technologies such as the Convertech process (Arnoux et al. 1994)

5. A more comprehensive model will include the possibility of recycling.

6. An example of this is the Biosphere 2 project that aimed to replicate a small ecosystem to sustain life. The results of this highlighted the many unexplained features of the ecosystem.

7. The particulate matter comes from local industry and housing.

Part 3: Application of physical models

Chapter 12: Introduction to the ECCO[1] methodology

This chapter summarises the ECCO modelling methodology developed by Malcolm Slesser and his colleagues over the last 15 years. Much of the initial work on the physical model developed in previous chapters was inspired by the ECCO methodology. ECCO is designed to be applied to individual countries to estimate physical limits of economic growth. Based on system dynamic modelling of energy and economic flows within an economy, the methodology was developed by Slesser in the early 1980s in association with UNESCO and FAO. The purpose of the model is to investigate issues of physical limitations on long term population-economy-environment-development issues associated with growth of economies. The method has been applied to economies as diverse as Kenya (Owino, 1991), China (Wenhua, 1991 and Xiaohui, 1995), Zimbabwe (Ruboko, 1991), Thailand (Sintunawa, 1991), Mauritius (Baguant and Slesser, 1991), the UK (Slesser et al., 1994), the Netherlands (Noorman, 1990, 1995), France (Meral et al. 1994, Faucheux et al. 1995) and to the global economy (King and Slesser, 1992). This chapter briefly outlines the logic behind the methodology and describes several problems experienced with the models. Possible solutions to these problems are discussed in the following chapter. Applications of the model along with comparisons with conventional economic models and the limits to growth models of Meadows et al. (1973) are also discussed.

1 An overview of the ECCO methodology

The model is designed to account for dependencies between different sectors of the economy and the environment. Conventionally, the economic and the environmental are analysed separately with no feedbacks between the two. The result of this is that one only gets a partial view of the effects of economic growth on the ecological system (Schembri and Zyla, 1993). The ECCO model is based on system dynamics that allows complex dynamic processes to be simulated such as delays and nonlinear feedbacks.

The ECCO methodology focuses on biophysical throughput, via a resource accounting method that calculates the resource requirements of an economy for a given pattern of activity, growth and technology. The key question that ECCO is designed to address is *"how large can an economy get, and at what rate can it expand?"* The aim of doing so is to clarify questions about the existence of, and characteristics of, possible physical limits to growth in biophysical throughput.

1.1 Types of natural capital

King and Slesser define three types of natural capital[2]:

-depletable (i.e. non-renewable energy resources)

-recyclable (i.e. non-energy mineral resources), and

-renewable or potentially renewable, (i.e. life support systems)

This set of definitions is similar to those discussed in Chapter 7. The capital that has the potential to limit economic growth is the depletable natural capital (non-renewable energy). Slesser argues that: "the limiting rate of change of the system is the rate at which energy can be *usefully* absorbed by the economy" (Slesser, 1992, p. 2). Any effort to expand the energy systems in the economy will require other inputs of energy. Therefore, energy analysis is an important tool for analysing long term economic growth. Energy analysis, as defined by the IFIAS convention, is used to quantify the amount of Depletable Natural Capital (DNC) required to achieve any particular economic activity. As described below, this form of energy analysis is the basis of ECCO.

1.2 Time period of the model

The model is designed to test simulations up to 30-70 years in the future. A model designed for this time span cannot be expected to reflect short term fluctuations in economic activity. Resource accounting models such as ECCO are generally constructed on the assumption that fiscal and related economic factors are not an obstacle to growth.

That is, they are based on the assumption that everything produced is sold, there are no employment or inflation-related problems, and there are no social restrictions on growth. Standard economics generally studies growth of the economy within assumptions that resources and pollution sinks will be available. In ECCO, the opposite approach is taken, by assuming no "economic" limits but addressing possible physical limits. Physical limits constrain economic possibilities.

An ECCO model does not lend itself to optimisation of utility, energy or anything else. It is a simulation model for testing possible scenarios. Once the physical assumptions are stated the model can be run to find the maximum rate of expansion for that set of physical parameters. An alternative modelling philosophy is described in section 3 in the next chapter.

1.3 Stocks and flows in ECCO

ECCO models place particular emphasis on calculating stocks of capital and the rates at which they accumulate and deplete. It takes time for quantity and quality of these stocks to change and this introduces an important dynamic limit on scenario options. For example it takes time for energy efficiency technologies to replace existing capital stock. Calculating the capital, rates of capital formation and depletion also helps to understand physical flows within the economy. For example, some types of solid waste will be proportional to the rate of capital depletion that in turn is dependent on the life time of the capital.

All flows are related by feedback loops. For example, fuel is used by the very industries that supply fuel to the economy (this is called the energy requirement for energy or ERE in ECCO models). It may be that ERE increases as the quality of resources mined declines. Any increase in fuel demand from the economy will require the energy sector to expand which in turn will increase ERE. To continue the example further, increased quantities of capital may be required to expand the energy sector. This must come from the industry sector that also requires an increased energy input. These, possibly nonlinear, feedback loops ensure that all physical flows are accurately calculated for each scenario. Detailed structural information is found from input-output tables[3].

The input-output structure of the model allows the production inputs to be simulated. For example, to make a unit of industrial output requires inputs from all sectors of the economy. Many products produced within the economy are intermediate products that are then the input to another production process. This type of analysis is very important when investigating changes in the structure of the economy. Because ECCO is a systems dynamic model it has several advantages over a static input-output analysis, including the ability to include feedback loops, delays and capital stocks. It is also much more flexible in the types of scenarios that can be investigated.

The models can be built using any of the standard simulation software packages such as Dynamo, Stella and Vensim[4]. These packages enable feedbacks and nonlinearities between variables to be simulated which allows the modeller an enormous amount of flexibility when developing scenarios.

1.4 Growth in ECCO models

Growth in ECCO models is determined by the amount of capital that is available in different sectors of the economy. If, for example, the capital requirements in the energy sector increase then there will be less capital available for investment or consumption. This is based on classical growth theory and the difficulties with this were discussed in Chapter 9. This problem is discussed in more detail with reference to ECCO in the following Chapter.

1.5 Resource availability in ECCO models

A stated above, resource availability in ECCO is based on the Ricardian concept of changing resource quality rather than the Malthusian idea of limited resource quantity.[5] It may be assumed, for example, in an ECCO model, that the quantity of depletable resources available to an economy is effectively infinite. The *accessibility* of that resource is, however, limited in practice by the amount of energy and capital required to make it available to the economy.

1.6 Pollution in ECCO models

The ECCO type of model is not used to predict what will happen in the future. It is used to test various proposed or possible scenarios of future development. If a "business as usual" scenario is proposed, then a model can show which specific technological, resource and pollution assumptions are required to make it possible. Similarly, a switch to solar energy presupposes a number of assumptions. Once these (physical) technological assumptions are explicitly identified, they can hopefully be rationally debated. Similarly, useful indicators of sustainability may emerge from comparing the required assumptions to the actual situation over time.

2 Embodied energy as a numeraire

A discussion of the use of money as a numeraire is required to understand why Slesser and his colleagues have chosen energy as a numeraire. The problem with using money for a physical model is that money obeys no physical laws. There are no physical restrictions on the printing or destroying of money. It can flow around an economy with no losses. Money can grow exponentially *ad infinitum* in a compound interest account. These properties of money are different from those of the physical goods and services money is supposed to represent. There is a need for a more physical or "real" unit to describe the economy, in order to address questions of the type central to our study.

If one analyses the economy using money as a numeraire there are no obvious limits to economic growth. Chapman and Roberts comment that:

> One immediate consequence of the use of value is that the economic concept of efficiency does not have any obvious limit of constraint in the way the engineering efficiency does (Chapman and Roberts, 1983, p 79).

For example, the cost of making a tonne of steel can in theory decrease for ever.

However, the amount of energy required to produce a tonne of steel is constrained by the laws of thermodynamics. Using energetic units of measure is a convenient and scientifically robust way to express a physical understanding of economic activity and to expose the significant biophysical constraints on economic system activity through time.

Given the difficulties with the use of money as a numeraire Slesser has chosen embodied fossil energy, as it is a measure of the depletable resource cost of economic activity. The reason that Slesser has chosen embodied fossil energy is that:

> Physical resources, with the possible exception of helium and mercury, are so abundant in the earth's crust that mankind cannot conceivably run out of them. Furthermore though they may be used, unlike energy, they are never used up (Slesser, 1991, p 41).

Therefore, energy is the key limiting factor to economic growth. Given enough energy other resources can be made available.

Capital stocks and flows in ECCO models are measured by the amount of embodied fossil energy required to produce them:

> ...one may logically measure economic activities in terms of only the energy required to make them happen, so long as one takes account of past as well as present energy (Slesser, 1990, p 27).

The choice of numeraire is discussed in more detail in the following Chapter.

2.1 Measuring embodied energy

Slesser's approach, following the IFIAS convention (Energy analysis, 1974), is to measure only the depletable energy resource consumption associated with making a good or service available to final demand. The flow of solar energy to the economy is indirectly included in ECCO models via the limited amount of land available (hence limited agricultural and solar production). Fuels derived from solar flows are measured in terms of the amount of embodied fossil energy required to build and operate the capital structures needed to supply this solar energy (eg hydro dams and wind turbines). Embodied fossil energy represents the "depletable natural capital" requirement of economic activity and hence gives an indication of sustainability of the economy.

Emphasis is placed on embodied fossil energy because any switch to solar energy will require capital that in turn will require significant quantities of embodied fossil energy. It is the dynamic problems that come about in the transition from one fuel type to another (especially from depletable to renewable) that can be profitably investigated by the ECCO approach. In other words, "Is there enough time for a transition to renewable energy systems before the scarcity crunch comes (King and Slesser, 1992, p. 9)?" This comment also relates to the fact that the "scarcity crunch" is at least as importantly associated with the scarcity of pollution sinks, for example that associated with carbon dioxide emissions, as with scarcity of resources such as oil or gas.

3 Application of ECCO models

There are two potentially important applications of ECCO, global and national. Global ECCO models are useful for investigating theoretical problems of long term limits. It is difficult to do the same type of analysis with national economies due to their dependence on the global economy, but it is possible to gain useful information at a national level that may aid policy analysts.

The aim of a global model is to investigate physical limits to economic growth. The type of question that this type of model could give insights to are: Can the transition from fossil to renewable energy proceed while maintaining current material standards of living? What technological assumptions are required to make the transition? How realistic are these technological assumptions? What assumptions need to be made about pollution feedbacks? A simple global model is developed in Chapter 14 that incorporates a number of methodological improvements outlined in the following chapter.

In national modelling, ECCO has the potential to be used for medium to long term energy and carbon dioxide projections. The dynamics of structural changes caused by a significant shift in energy production technologies can be modelled using ECCO. Data on the structure of the economy and initial energy intensities have been found using input-output data. ECCO models of the New Zealand economy are described and discussed in Chapter 15 and 16.

4 Relationship between ECCO and other economic models

Describing the differences between ECCO and other economic models clarifies the different purpose and hence different role the model has in analysing the economy. ECCO is here compared to conventional econometric models and the Limits to Growth models of Meadows et al.

4.1 Comparison of econometric and ECCO models

It is important to understand how ECCO type models are different from the econometric models discussed in Chapter 4. It should be noted that the econometric models aim to achieve an extraordinarily difficult task. The purpose of ECCO is not to analyse human behaviour but to analyse physical flows in the economy. The models developed in this thesis are not directly comparable to econometric models as the questions they aim to answer are significantly different. To compare ECCO to econometric models is comparable to comparing a circular saw to a chain saw. Both are designed for different purposes so one cannot say which is better. The important thing is to state the different purposes and not try to use one sort of model for a purpose that it was not designed for. Table 12-1 describes the differences between ECCO and econometric models. ECCO will not replace conventional economic analysis but it is a complementary tool to add a different perspective to the understanding of the economy and the environment.

Model type	Econometric	Physical (ECCO)
Time frame	Short (0.4-5 years)	Long (30-70) years
Unit of interest	Human behaviour	Physical flows
Numeraire	Money	Energy
Structural assumptions[6]	Static	Dynamic
Critical factors	Inflation, prices, interest rates, wages, employment, business confidence, etc.	Resource efficiencies, capital requirements, technology, environmental assumptions

Table 12-1 Difference between ECCO and econometric models

A common question about ECCO is "how does this help predict prices?" The answer is that it does not, since the model is not designed to. The model calculates structural changes and associated physical flows and technological assumptions. These can then be compared to historical values to see if the scenario is physically realistic.

4.2 Comparison with "Limits to growth" type models

A comparison must be made with the "Limits to Growth" models of Meadows et al. (1972, 1992). While in a number of important respects the ECCO approach builds on the modelling philosophy developed by these authors (in turn pioneered by Forrester, 1971), it is also different in some key ways.

As already pointed out resource limits in ECCO are based on the Ricardian idea of diminishing quality and accessibility of resources, rather than on the Malthusian concept of fixed resource stocks. Secondly, energy is specifically identified as the key non-substitutable resource that deserves special treatment. Thirdly it places a major emphasis on the role of technology and how it changes over time. In modified ECCO models, the rate of technological change can be related to energy requirements.

ECCO could be subject to the same criticisms levelled at the "Limits to Growth" models, in that it does not have price mechanisms that would encourage substitutions within an economy. The theory behind substitution is that if resources become scarce prices will go up, consumption will fall and substitutes will be found. If future prices and elasticities can be estimated, then changes in supply and demand can be predicted. ECCO cannot predict anything, however; it can only test scenarios. In conventional economic models it is highly debatable whether elasticities and prices can be predicted with enough accuracy to predict change in supply and demand in the long term anyway. ECCO essentially skips the step of using a scenario specified by prices and elasticities and instead uses a scenario specified in terms of demand[7]. So ECCO can be used to analyse any particular scenario including scenarios that have a large amount of substitution.

The first ECCO models had the same modelling philosophy as that of the Limits to Growth Models in that they attempted to make as much as possible of the behaviour of the model endogenous. The following Chapter describes a different way of applying the models, that may make communication of their results easier.

5 Summary

The ECCO modelling methodology is a novel and potentially very useful tool for investigating long term economy-environment interactions. The systems dynamics approach to the problem allows a great deal of flexibility with the scenarios that can be investigated. The emphasis of the ECCO model is on the accumulation and depletion of capital stocks and the associated energy flows. Because the model aims to look at relatively long term questions it has a different structure from conventional economic models which have a much shorter time frame.

The approach aims to identify possible limits to growth and hence there is a detailed analysis of the flows of depletable natural capital (in particular, embodied fossil energy). Measurement of these physical flows helps understand the possible long term physical limitations on growth. Because the model includes detailed input-output information, the effects of changing structure of the economy and the associated resource and pollution flows this would cause can be investigated.

The model does not forecast how the economy will grow but it sets an envelope of physically possible options within which the economically and politically optimal will lie. Any number of scenarios can be simulated, and the model calculates the associated physical flows so alternative scenarios can be compared to see what different physical assumptions are required.

Notes

1. ECCO is an acronym for *Evolution of Capital Creation Options* or *Evaluation of capital creation options* or *Energy and capital creation options.*

2. These definitions are similar to those developed in Chapter 7

3. See Chapter 15 and Appendix 2 for more details.

4. To date most ECCO models use the Dynamo simulation software (Pugh, 1991).

5. Some of Slesser's models include a stock of resources that declines in quality. In this case quality is a function of the quantity of resources remaining. This can easily be changed to remove the Malthusian concept of constant stock. The quality is then a function of cumulative production.

6. This refers to the input-output structure of the economy. When economists refer to the changing structure of their models they are talking about changes in the significant relationships within the model such as changing elasticities (Bacon, 1988, p. 138).

7. In the author's opinion, ECCO could be developed further so that it runs in parallel with more conventional economic models.

Chapter 13: Methodological issues relating to ECCO

The ECCO models developed by Slesser and his colleagues have two important weaknesses. These relate to the way that embodied fossil energy is defined and used as a numeraire, and to the growth algorithm determining the split between consumption and investment. Each of these weaknesses will be explained, and, in each case, a method offered for overcoming the difficulty.

Growth theory is discussed in Chapter 9 and this discussion on the growth theory of ECCO builds on that. The problem with the ECCO growth algorithm relates to the method of allocating industrial output between investment and consumption. If the fraction of industrial output not consumed is high, then industrial output will grow at a high rate; if the fraction not consumed is low, industrial output may fall. It is not clear what determines this "fraction not consumed," or fraction invested, in ECCO models constructed to date. The choice of the fraction invested implies a certain rate of technological progress, and this rate of technological improvement may in fact be the critical limit to growth. The model can be modified to make these issues explicit. The growth algorithm is also modified to allow for changes in the productivity of capital.

The second significant problem with ECCO models to date relates to the use of embodied energy as a numeraire. The embodied energy of goods and services does not necessarily correlate directly with the volume of economic output, as the quantity of embodied energy required to produce economic output changes over time. This means that embodied energy is not a reliable measure of economic activity. Prices do not measure economic output accurately, and must be converted into "constant dollars" to give a dimensionless index of the volume of economic production[1]. Similarly, embodied energy can be converted into "constant embodied energy" to give a dimensionless index of the volume of production. In this way both economic activity and the embodied energy required to produce economic output can be measured, without assuming they are the same thing.

Both of the recommended changes cause a significant change in the behaviour of ECCO models and the type of information that can be found from them.

1 Modelling economic growth

What determines the rate of economic growth in ECCO models? The most significant determinant of economic growth in an ECCO model is the fraction of industrial output that is reinvested in industry. In ECCO this is called "fraction not consumed" (FNC) and it may also be called the "fraction invested." Small changes in assumptions about the fraction invested have a huge effect on the growth pattern of the model. An understanding of the physical assumptions behind changes in the fraction invested can be found from an analysis of economic growth theory in Chapter 9.

1.1 Growth in ECCO models

The discussion on growth theory helps to understand the growth algorithm in ECCO. The following discussion briefly describes how ECCO models are set up to grow[2]. Figure 13-1 shows the influences that determine the growth rate in ECCO. The rate of investment in environmental services (RCFES) is set by the physical requirements of the environment and is essential for the running of the economy. Environmental services include energy, resources, water, pollution control and agriculture. The amount of

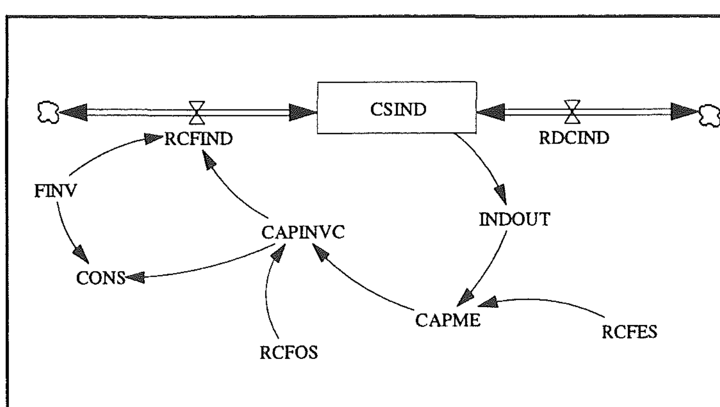

Figure 13-1 *Influence diagram of the growth loop in a simple ECCO model*

industrial output that is left can be used in the main economy.

CAPME = INDOUT - RCFPES

CAPME	Capital available to the main economy.
RCFES	Environmental services (energy, materials and agriculture).
INDOUT	Industrial output

The capital available to the main economy (CAPME) is to be split between consumption and investment in industry and other sectors such as transport, services etc. Of particular interest is the quantity of capital invested in industry, as this provides capital for the growth of the rest of the economy. It is for this reason that the capital requirements in other sectors (RCFOS) of the economy are subtracted from CAPME to leave the industrial output that is available for investment back into industry or consumption (CAPINVC).

CAPINVC = CAPME - RCFOS

CAPINVC	Capital available for investment or consumption
CAPME	Capital available to the main economy
RCFOS	Rate of capital formation in other sectors (transport, services etc.)

The rate of capital formation in industry (RCFIND) and consumption (CONS) may be a fixed proportion of CAPINVC or can be set up to change according to any particular scenario. The theory is that as investment increases, consumption will also increase, and vice versa. It may also be set up so that RCFIND may not drop below a certain level - as a policy decision. Consumption must drop accordingly to allow this to happen. Alternatively, money could be borrowed or repaid from overseas to allow capital to be imported.

CONS = (1-FINV) * CAPINVC

CONS	Consumption
FINV	Fraction invested[3]
CAPINVC	Capital available for consumption or investment

RCFIND = CAPINVC * FINV

RCFIND Rate of capital formation in industry

Small changes in the value of FINV vastly alter the rate at which INDOUT grows. If consumption is small, the amount available for investment will be large and INDOUT will grow rapidly. Conversely, if consumption is sufficiently large and there is little available for investment, then over time industrial output will fall.

The problem with this algorithm for growth is that it is based on classical growth theory that states that the amount of capital saved (saving rate) is the main determinant of growth. The discussion in Chapter 9 suggests that changes in labour productivity via technological change may also be a major determinant of output growth. If, and in the origional ECCO models, growth is made explicitly dependent on the fraction of total capital output reinvested, then it is important to identify what is implied about technological change (as indicated by productivity changes) in order that a specified growth rate might be attained. A growth algorithm that addresses this issue is developed below.

The other important feature about the ECCO growth algorithm presented here is that it attempts to make growth an endogenous function in the model rather than having the growth rate exogenously determined:

> In the ECCO approach, a link is made between the final demand for consumer goods, and the rate of growth of industry. This constitutes the major negative feed back loop that moderates the positive feedback loop of the human made capital production cycle (Slesser et al. 1995).

This link is the main reason industrial output declines, but the link seems arbitrary and in the author's opinion it cannot be justified as a strictly physical restriction[4].

1.2 Alternative growth algorithm

The most significant problem experienced with the growth algorithm in ECCO, as developed by Slesser and others, is that assumptions about technological change (labour productivity change) are not explicit. In effect, the growth of the model follows the emphasis of classical growth theory that emphasises fraction invested as the main determinant of growth rather than the neoclassical emphasis on technological change. To illustrate the advantages of including concepts from the neoclassical tradition a model is developed that clarifies assumptions about labour productivity (technological change). For simplicity, we assume that the population and hence the labour available is constant.

1.2.1 Calculating the assumed increase in labour productivity

Figure 13-2 is an influence diagram used to demonstrate the assumed change in labour productivity for different growth scenarios. From the initial conditions the growth over one year can be calculated. From this, the assumed improvements in technology can be calculated. The initial conditions and key equations for this model are as follows:

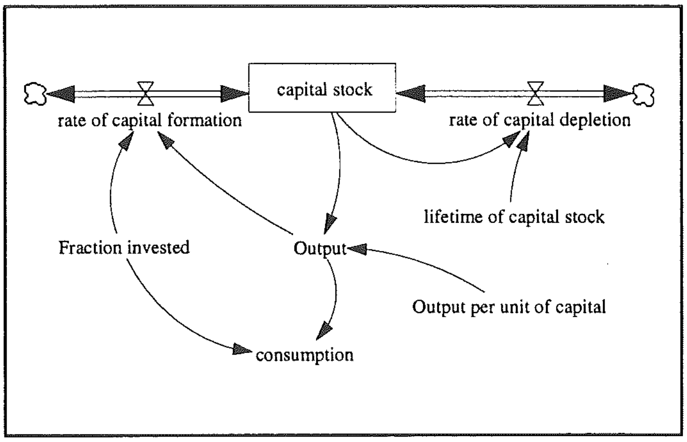

Figure 13-2 *Influence diagram of a model to demonstrate the implicit assumptions about technology (labour productivity)*

Initial conditions:

-Capital = 2000 units

-Output per unit of capital = 0.2

-Life time of capital stock = 40 years

-Fraction invested = 0.4

-Labour = 200 units

From these initial conditions, output, consumption and capital formation and depletion rates can be calculated:

Output = Output per unit of capital * Capital

= 2000 * 0.2 = 400

Rate of capital formation = Output * Fraction invested = 400 * 0.4 = 160

Consumption = Output * (1 - Fraction invested) = 400 * (1-0.4) = 240

Rate of capital depletion = Capital / Lifetime of capital stock = 2000 / 40 = 50

After one year the new capital stock and corresponding output can be calculated:

New capital = old capital + rate of capital formation - rate of capital depletion

= 2000+160 - 50 = 2110

New output = New capital * output per unit of capital

= 2110 * 0.2 = 422

Labour = 200 units (This is assumed to remain constant)

In this model the Fraction invested directly affects the output that can be produced. That is, a higher Fraction invested will lead to a higher growth in output. However, it is not apparent from the model as written that there is the implicit assumption of an increase in labour productivity (technological change). This change can be calculated by comparing the labour productivity after one year.

The average labour productivity of the capital is:

Output / Labour = 400 / 200 = 2 units of output per labourer

The average labour productivity of the total new capital is:

New output / Labour = 422 /200 = 2.11 units of output per labourer

The average percentage labour productivity increase is

((2.11 - 2) / 2) * (100/1) = 5.5%

This calculation shows that it is an implicit assumption of the model that the average labour productivity increases at 5.5%. This type of assumption is not explicitly made in ECCO models, yet improvements in labour productivity may be an important limitation.

1.2.2 Calculating the implicit assumption about labour productivity of new capital

Another interesting hidden assumption of the model can also be calculated. That is, how much more productive the new capital must be, compared to the capital it is replacing. The rate of change of the capital stock influences how much more productive the new capital must be. If capital is changing slowly (high life time of capital) then it is more difficult to change the average productivity. To calculate the labour productivity of the new capital the labour required to run the new capital and the output produced from the new capital must be calculated.

Labour force available to run the new capital is assumed to be equal to the labour used in the capital it is replacing:

Labour force of new capital = Labour * (Rate of capital depletion / Capital)[5]
= 200 * (50/2000) = 5 units of labour

Output of the new capital is the difference between the new and old output plus the output that would have been produced by the old capital:

Output of the new capital = (New output - Old output) +
(Old output*(1/life time of capital stock))
= (422 - 400) + (400/40) = 22 + 10 = 32 units

The labour productivity of the new capital must be:

Output of the new capital / Labour force of the new capital
= 32 / 5 = 6.4 units of output per labourer

Therefore the percentage increase in labour productivity is.

$$((6.4 - 2) / 2) * (100/1) = 220\%$$

This calculation shows that the labour productivity of the new capital must be 220% better than the labour productivity of the capital it replaced. These underlying assumptions are not obvious from the simple growth diagram in Figure 13-2. These technological coefficients may be the critical limiting factors on long term economic growth, so they must be explicitly calculated for each scenario.

These simple calculations can be added to the ECCO models, to indicate the assumed increases in labour productivity that are implied by changing the saving rate. It should be noted that, if the labour force increases, then the influence of this on labour productivity can also be calculated. In this case, output will be able to increase faster, for a given increase in labour productivity. However, output per person will not increase at a faster rate. More advanced models can include demographic data on the fraction of the population that is in the labour force.

This relatively simple addition to the ECCO model makes some of the critical underlying assumptions explicit. It is still, however, not sufficient, as it does not model the process of changing the output to capital ratio.

1.3 Changing output to capital ratio

In the model above, output is a fixed proportion of capital stock. In reality this may change, as capital requirements usually increase as labour productivity increases. This process is called "capital deepening" (Solow, 1988). Capital deepening decreases the output per unit of capital, and ECCO needs to be able to model this. One way of doing this is to keep track of the extra capital separately, in a different set of accounts. Figure 13-3 illustrates how this can be achieved. Output is still a direct function of the capital stock, but this capital stock is equivalent to what it would be if there is no change in the cost of capital. Any extra capital required to improve the labour productivity is accounted for separately in the adjusted capital stock. The capital available for investment is now split between the main capital account (Capital stock) and the Adjusted capital stock.

This new model is best illustrated by further developing the previous example. It was shown that a fraction invested of 0.4 implied a labour productivity increase of 5.5%. If one assumes that this increase in productivity can be achieved with capital at the same cost as that which it replaced, then the adjusted capital would be 0. If, however, the capital cost an extra 10% per unit of output, then this is added to the adjusted capital stock. The output is still directly proportional to the main set of capital, but the total capital required to produce the output has increased. Therefore, the overall output to capital ratio has decreased. If this additional 10% of capital were added to the existing capital, a new output to capital ratio would have to be calculated. It is easier to keep track of this productivity-increasing capital by accounting for it separately than by changing the output to capital ratio.

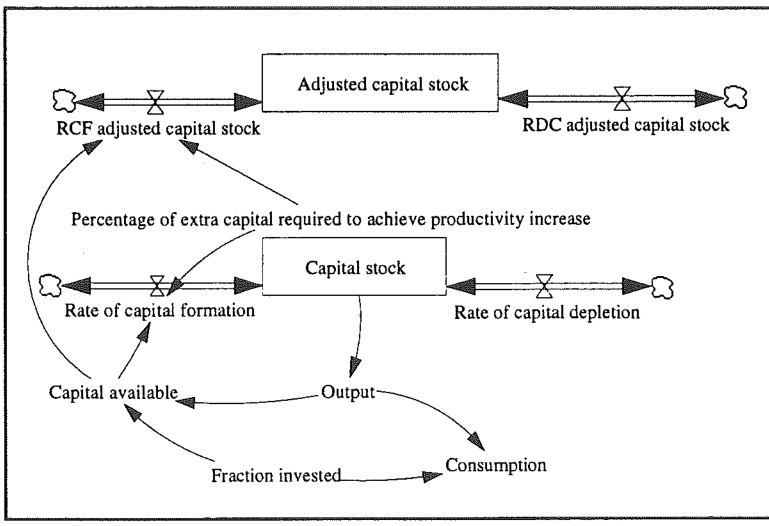

***Figure 13-3** Economic growth model with two sets of capital to allow for capital deepening*

1.4 Changing energy efficiency of capital

Another example to illustrate why capital stocks are calculated separately is the changing energy efficiency of the capital stocks. In ECCO energy demands are proportional to capital stock. If some new, more expensive, energy saving technology is used, then this will decrease the direct energy required. If, however, the energy demand is proportional to the capital stock and the additional expense of the capital increases the total capital stock, then the model will not calculate the new energy demand correctly. Instead, the extra expense of the capital stock should be added to the Adjusted capital stock. In this way, the additional cost of capital will not artificially increase capital stock and hence energy demand.

This difficulty of changing efficiency of capital is highlighted by the arguments of Crane (1995b). In his paper Crane argues that increased investment in energy conservation causes increased income that in turn increases the total energy demand (the "rebound" effect). In fact what happened in his model is that the capital increased and because all energy demands are proportional to capital stocks it appeared that the energy demand increased. This could be easily tested by simulating the model and assuming that the energy efficiency required no extra capital. One would expect the rebound effect to be stronger in this case as incomes would be even higher but it showed that the rebound effect virtually disappeared.

1.4.1 Changing the life time of the capital stock (durability)

The model developed here shows the interesting dynamic implications of changing the lifetime of the capital stock. In a classical growth model, increasing the life time of capital will improve the growth of the model, as less must be saved to increase the capital that in turn increases the output. With neoclassical growth theory, where productivity changes are permitted, if the life time is short it allows a higher rate of capital turn over which allows a faster increase in average productivity so a lower life time will tend to increase the growth rate. The life time of capital has other implications from a sustainability point of view (i.e. resource use and pollution output). For a given savings rate, changing the life time of capital changes the extent to which new capital has to be better than existing capital, to achieve the productivity increase. If the life time is long, then the rate of capital turnover is long, so the new capital has to be much better than existing capital to influence the average capital productivity.

1.5 Finding a realistic growth scenario.

So how does the above discussion help determine a realistic growth scenario for an ECCO model? An example of the iterative development of a scenario is as follows. In the case above it may be found that the historical rate of technological (labour productivity) advance is 2%. However, when the fraction invested is 0.4 there is an implicit assumption of a 5.5% increase in labour productivity. From this, it may be proposed that the fraction invested is probably unrealistically high. To attain a realistic growth rate the fraction invested (FINV) can be adjusted until the overall growth rate in labour productivity is about 2%. This method means that an unrealistically high fraction invested will immediately show up through high assumed increases in labour productivity, and the model can be adjusted accordingly if these labour productivity increases cannot be justified. Similarly, the fraction invested may be too low which may cause an unrealistically low or negative labour productivity rate. Either way the modeller has to justify their assumptions about technology.

The problem with the ECCO growth algorithm of Slesser is that it does not acknowledge the implied technological (labour productivity) change required for different growth scenarios. These factors need to be calculated in the model and the resulting productivity changes must then be justified as part of the simulation. The other modification to growth in ECCO is to allow for a changing capital to output ratio. Previously, changes in the cost of capital would influence demands in the model, as they are proportional to the capital stocks. The new method accounts for changes in the quantity of capital separately so it does not change the energy and resource demand in the model.

2 Problems with embodied fossil energy as a numeraire

In the ECCO methodology all economic output is measured in terms of the quantity of fossil energy required to produce it. This embodied energy is a measure of the level of economic production. Through using ECCO to develop a model of the New Zealand economy, the author has found that using embodied energy to measure economic output has a number of difficulties. As an example, in some simulations the quantity of fossil energy required to produce electricity changes dramatically and this affects the embodied energy in all economic outputs[6]. While the embodied energy of the outputs changes significantly, the actual outputs do not. There needs to be some method of distinguishing between the embodied energy of economic output and the quantity of economic output; they are not the same.

2.1 Changes in the embodied energy to output ratio

There many different ways in which the embodied fossil energy required to produce a good or service can change over time. For example, the quantity of embodied fossil energy required to transport goods a certain distance can change due to a number of factors.

Technological/social factors that affect the output to embodied energy ratio:

- technology may improve, eg a more efficient engine is used for transporting goods.
- technology may change, eg a train may be used instead of a truck.
- the way a technology is used may change, eg a driver may be educated to drive at optimal speeds and accelerations to conserve energy.
- the proportion of energy coming from renewable sources may change, hence the embodied fossil energy will change, eg biomass methanol used as fuel in a truck.
- the amount of labour used may change, eg goods may be transported by bicycle.

Physical factors that affect the output to embodied energy ratio:

- more (or less) energy may be required to retrieve the fossil energy, hence the embodied fossil energy in the fuel will have changed.
- more energy may be required to provide the materials required for a specific task, eg the energy to produce steel to make a truck may change.

- more energy may be required to treat pollution, eg a catalytic converter may be required, which may increase the amount of energy used for a specific task.

In each of these cases, the amount of embodied fossil energy required to achieve a task will change. These changes need to be included in any model, so embodied energy can be related to a volume index of production. It may not be easy to predict how the relationship between embodied fossil energy and the quantity of production changes over time, but the first aim is to develop a model that can incorporate such changes. The next stage is to investigate how the embodied energy to output ratios of each sector are likely to change, by looking at historical trends and future technological options.

2.2 Embodied energy as a numeraire in ECCO

The problem with the current ECCO methodology is that growth in biophysical throughput (embodied energy) is assumed to be the same as production (see previous Chapter). However, the examples listed above illustrate a number of ways that the embodied energy to output ratio can change. The analysis of Cocklin et al. (1989) illustrates significant changes in embodied energy per unit of output in different sectors of the New Zealand economy over ten years. More significant, however, are the large changes in embodied fossil energy that will occur with a switch to solar energy technologies. Given that changes in the embodied energy to output ratio can happen for many different reasons, a method to account for the difference must be included in a model that uses embodied energy as a numeraire to measure production.

This problem of embodied fossil energy not representing physical output is a key issue with the methodology. It is worth explaining in detail, using a simple hypothetical economy. The problem is perhaps more obvious when one does some simple dynamic simulations. The simplest model for which the embodied energy problem can be demonstrated is shown in Figure 13-4. This is a single sector economy in which industrial output is assumed to be either consumed or reinvested to make more

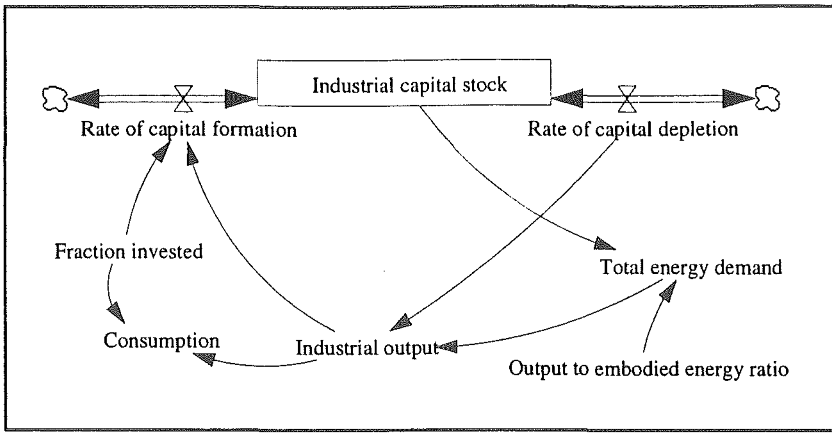

Figure 13-4 Economic growth model using embodied energy as a numeraire

industrial output[7]. In this model the "Industrial capital stock," "Industrial output" and "Consumption" are measured in terms of embodied energy. The embodied energy of "Industrial output" is the sum of "Total energy demand" and "Rate of capital depletion."

Industrial output = Total energy demand + Rate of capital depletion GJ

For simplicity the fraction invested is held constant which means that industrial output grows at a constant rate.

Consumption = Industrial output * (1-Fraction invested)

Rate of capital formation = Industrial output * Fraction invested

The graph in Figure 13-5 shows the growth of consumption and industrial output if the "Output to embodied energy ratio" remains constant.

If the amount of energy required to produce a unit of output changes, for any of the reasons listed above, then this will affect the growth rate of the model. To illustrate this point, assume that the "Output to embodied energy ratio" changes from 1 to 0.5 over a 100 year period. The effects of this single change on "Industrial output" and "Consumption" are shown in Figure 13-6. The reason for the decline is that the embodied energy in industrial output has fallen. There is therefore less industrial output available for investment, which reduces the rate of growth of "Industrial capital stock," and this in turn reduces the quantity of "Industrial output" produced.

There is no doubt that the amount of embodied fossil energy required to produce goods can change. A large investment in solar energy, for example, would cause a decline in the embodied fossil energy requirements of industrial output. In King and Slesser's analysis of the global economy (King and Slesser, 1994) the simulations involved a large scale switch to solar energy. These simulations showed a significant decline in industrial output. From the arguments given above, it may be that using embodied fossil energy as a numeraire was the main reason for the decline, rather than the increased investment required for solar energy, although it is difficult to say for sure without examining the model in detail[8]. Slesser et al. do acknowledge there are difficulties with changing embodied energy to output ratio, in particular with changing FEREL (fossil energy requirement for electricity), and his method of dealing with this is discussed below.

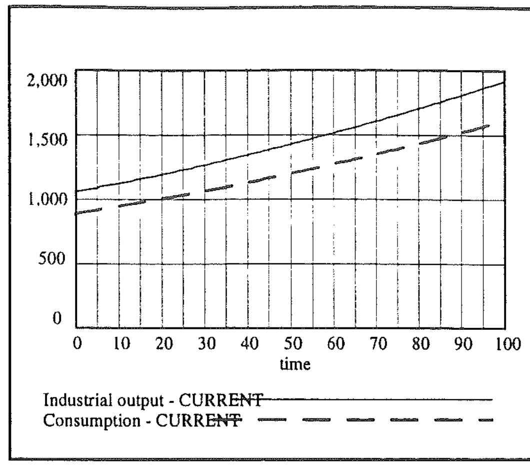

Figure 13-5 *Growth of "Industrial output" and "Consumption" with a constant "Output to embodied energy ratio."*

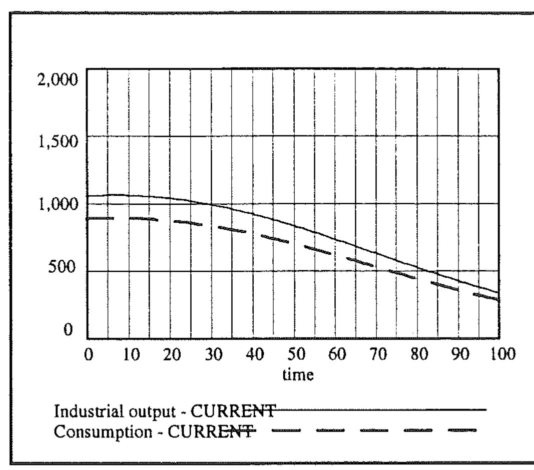

Figure 13-6 *Growth of "Industrial output" and "Consumption" for a decreasing "Output to embodied energy ratio."*

2.3 Modifications to ECCO - Double set of energy accounts

The following sections describe how the ECCO methodology can be modified, to adjust for the changing relationship between embodied fossil energy and economic output.

There are two indicators required from an ECCO type model; one is a measure of the level of activity in an economy, or a volume index of production; the other must give some measure of the sustainability of the economy. Given these, a numeraire must be chosen that will give the required information.

Any numeraire used to measure economic output must be able to compare apples with oranges. That is, it must be able to compare outputs that are completely different. Using money as a numeraire, the comparison is based on how much the average person is prepared to pay for a commodity in a marketplace. Comparisons between sectors indicate the relative human preferences for the goods and services. The main interest of economists is human behaviour and how preferences can be measured to determine what and how much of each different type of good and service should be produced. This is done by measuring preferences through market prices, and this in turn affects the supply and demand for economic goods.

The concept of constant dollars as a dimensionless index of the volume of production allows money to be compared over time. For example \$1 might have bought 1.5 kilograms of oranges in 1977 yet it cost \$3.52 to buy 1.5 kilograms in 1994. Clearly, the simple dollar values do not represent the volume of production. However (in the New Zealand context) the 1977 dollar value can be converted into 1990 dollars by the Producers' Price Index in the Food and Beverages sector. In this example \$1 in 1977 is equivalent to \$3.52 in 1994. In this way the real dollar value is not a measure of human preferences but is a dimensionless index of the volume of production. Economists take great care in calculating price indexes so that constant dollars are as accurate as possible an index of volume of output in the different sectors.

The use of money as a numeraire allows a quantitative estimation of human preferences and hence human behaviour in the short term. However, human preferences are not very good indicators of physical limits so a different numeraire should be used for a physical model. Energy is an important indicator of physical limits (Slesser, 1990, Peet, 1992). If energy (or embodied energy) is used as a numeraire the comparison between sectors shows the differences in relative "physical difficulty" rather than difference in human preferences. Associated with "physical difficulty" are important technological, resource and pollution assumptions.

Simple embodied energy no more represents the quantity of output than do simple (nominal) dollars. To compare outputs over time, the energy numeraire must be converted to "constant energy" in the same way that dollars are converted to constant dollars. Instead of using a Producers' price index to convert, the change in "embodied energy to output ratio" can be used to convert actual embodied energy to "constant embodied energy." This measure of "constant embodied energy" will represent a dimensionless index of production in the same way that constant dollars does. As in conventional economics, it does not measure the "value" of economic output, but is an indication of the physical level of that output, relative to a base situation.

The model based on energy is not designed to measure human preferences or behaviour etc. Similarly, a conventional economic model using money as a numeraire is not designed to show physical restrictions. However, they can be linked through the common concept of using constant units as an index of the volume of production. It should be remembered however, that such models have different purposes and hence are complementary.

Modelling an economy with only embodied energy and not converting it to some dimensionless volume of production is somewhat analogous to modelling with money and not taking account of inflation when comparing outputs over time. This is why it must be included in ECCO models.

2.4 A numerical example of constant embodied energy

The way in which "constant embodied energy" relates to embodied energy over time is best illustrated by way of a simple numerical illustration (Note: these figures are only used to illustrate our point):

In 1982 the level of activity in the transport sector may be 5 tonne kilometres.

The embodied fossil energy required to make this transport service available may be 1 GJ. If technology and everything else remained constant, the embodied energy measure would be an index of the output. Thus, if in 1992 the embodied energy was 1.2 GJ then the level of activity in the transport sector would be 6 (5*1.2) tonne kilometres.

In reality, the embodied fossil energy required for a task can change. As an example, assume that over ten years, due to changing technologies, the energy efficiency of the transport fleet increases by a factor of two. Assume for simplicity's sake that the only energy requirement of the transport sector is the direct energy requirement. Thus, the embodied energy requirement will have dropped by a factor of two. In 1992 the transport activity has increased to 6 tonne kilometres and therefore 0.6 GJ ((1.2*1GJ)/2) of embodied energy is required.

If embodied energies are compared directly (i.e. 0.6 GJ 1992 compared to 1.0 GJ 1982), it would appear that the transport output has dropped (remember ECCO measures outputs in terms of the embodied energy required to produce them). However, the equivalent 1982 GJ of the 1992 transport output is 1.2 GJ (the amount of energy required if all technological factors remain the same). If this "constant embodied energy" is compared to the 1982 value it shows that the output has increased by 20%. Thus, the relative level of economic activity is measured by the "constant embodied energy."

It can be argued that any increases in efficiency requires a capital input that in turn requires embodied energy. This is true in general, but it is not certain that the increase in efficiency is totally offset by the increased capital requirements to maintain a constant embodied energy to output ratio. In this analysis, the two factors are separated, since they are not rigidly connected.

By analysing both the "constant embodied energy" and the actual embodied energy, two important aspects of the economy can be measured. In the example above, the embodied fossil energy (EE) has dropped, showing that there is less reliance on depletable energy resources. The relative volume of output, as measured by the "constant embodied energy," has increased.

2.5 Growth model with a double set of accounts

Figure 13-7 is a modification of Figure 13-4 to include the double set of accounts. The industrial output is modified to account for the change in output to embodied energy ratio. The additional set of accounts is measured in embodied energy (EE). The capital stocks must be calculated separately as the embodied energy of the capital stock contributes to the embodied energy in industrial output.

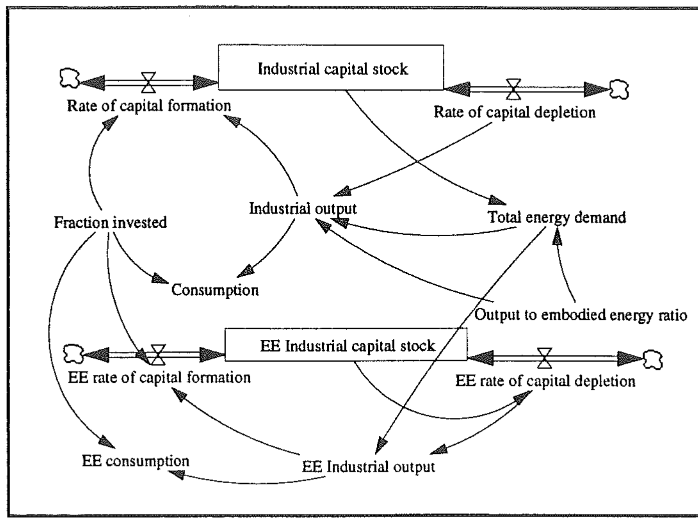

Figure 13-7 *Growth model with a double set of accounts to adjust for changing output to embodied energy ratio (CHAP147.VMF, see appendix 6)*

Figure 13-8 illustrates how "Industrial output" changes in the same scenario as in Figures 13-5 and 13-6. That is, the output to embodied energy ratio falls from 1 to 0.5 over 100 years. As one would expect, "Industrial output" increases at the same rate as before. However, the embodied fossil energy of industrial output decreases; this shows that the economy is becoming less dependent on energy. This method of using two sets of accounts has been used in the development of a global CORECCO type model and a

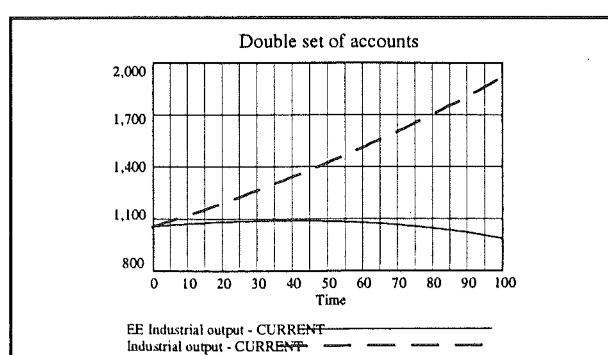

Figure 13-8 *Results of a model with a falling output to embodied energy ratio with a double set of accounts.*

national New Zealand model.

2.6 An alternative method to adjust for a changing output to embodied energy ratio.

Slesser acknowledges that some adjustment has to be made for the changing energy intensity to output ratio[9], or as he calls it energy intensity of industry (EII). His method of solving the problem is shown in Figure 13-9.

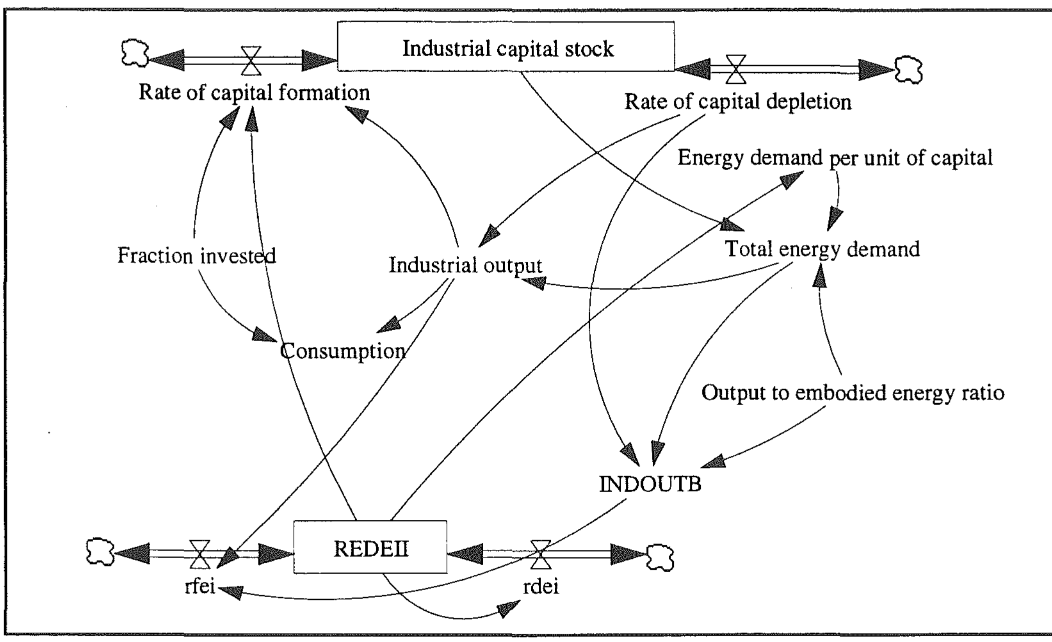

***Figure 13-9** Influence diagram showing Slesser's method of adjusting for changing Output to embodied energy ratio*

INDOUTB is a calculation of the embodied energy in industrial output as if the "output to embodied energy ratio" is constant. From this, a factor called reduced energy intensity (REDEII) can be found, REDEII = Industrial output / INDOUTB

> This coefficient REDEII is then introduced into every equation where there is a rate of capital formation, and has the effect of reducing the energy intensity of that capital (Slesser, 1995, p. 28).

In this case, Rate of capital formation = (Industrial output*Fraction invested)*REDEII
A further modification is required so that the energy demand is not artificially low due to the reduced capital stock (remember energy demand is proportional to capital stock).

Energy demand per unit of capital = 0.3 / REDEII

REDEII cannot be calculated as an auxiliary variable as there are simultaneous equations involved. Therefore, it needs to be calculated as a level variable[10]. The method attempts to solve the problem while not recognising that the embodied energy of industrial output and the actual level of industrial output are different.

Remember that the only change to the model is that the "Output to embodied energy ratio" changes. The simplifying assumption is that this has no effect on the amount of capital required, therefore this change should have no effect on the volume of "Industrial output" produced. The results of this simulation are shown in Figures 13-10 and 13-11 along with the results from the double set of accounts methodology described

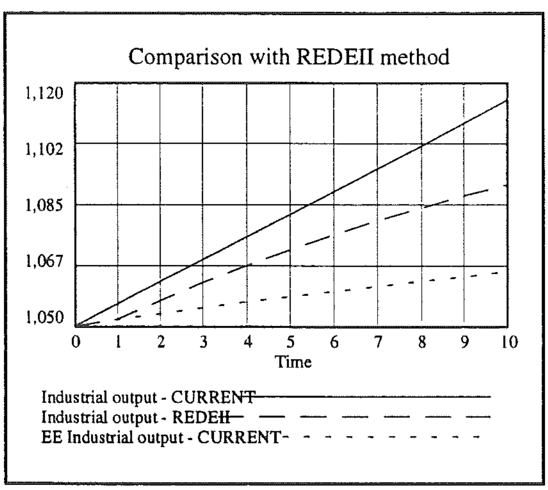

Figure 13-10 Comparison between the REDEII method and double set of accounts method to adjust for changing "Output to embodied energy ratio" over 10 years.

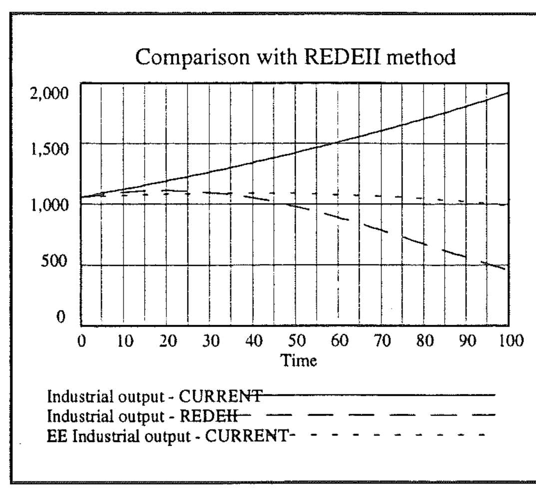

Figure 13-11 Comparison between the REDEII method and double set of accounts method to adjust for changing "Output to embodied energy ratio" over 100 years.

above. The first graph shows the results after ten years, and indicates that the methodology does partially correct for the change in "output to embodied energy ratio." The second graph shows, however, that there are considerable errors in the long term. The assumption about changing of the "Output to embodied energy ratio" is not unrealistically large if one is proposing a change to solar energy technologies. This discussion highlights a significant error in the ECCO methodology that needs to be corrected.

3 Scenario construction methodology

As with other systems dynamic modellers (Meadows et al. 1972) the aim of Slesser and his colleagues was to make growth in the models endogenous. In this way they could state the key physical assumptions, run the model and then see the results. The difficulties with this is that it appears that a prediction about the future is being made which many analysts find difficult to accept. It is difficult to communicate the difference between a prediction and a scenario (see Chapter 6). On top of that some of the underlying assumptions that determine the outcome of the model may not be communicated effectively. To get around these problems the same model can be used in a different way. The end point of any scenario can be stated and the model can be used to calculate the physical assumptions required for this end point to be reached. In this way there is no confusion about prediction and the modeller is then focused of identifying the critical physical assumptions and connections within the model. The type of assumptions will include things such as the quantity of food that can be produced on a given area of land, improvements in technology and assumptions about pollution feedbacks. Once identified these physical assumptions are then open for scrutiny. So if it is believed that the economy will get to a certain end point each of the specific physical assumption must be able to be justified. If the assumptions are questionable then a different scenario may have to be tried.

The main point of using the model like this is that it no longer appears to be a magical prediction tool but a tool that aims to identify critical physical assumptions about long term scenarios. This type of approach may make the model more acceptable to a broader range of people.

4 Summary

The ECCO methodology developed by Slesser and colleagues to analyse possible physical limits for the economy is novel and potentially useful. The methodology analyses the critical depletable resource flows through an economy measured by embodied energy. However, the output of the economy is not necessarily directly proportional to these flows, and the ECCO algorithms must be modified to separate embodied energy flows from production flows. This correction is analogous to the correction for inflation used by economists. The corrected figure will give a dimensionless index of the volume of production. Once this is done the model measures both the embodied energy and the actual volume of production of all flows in the economy. The embodied energy information is very useful for understanding the critical determinants of economic growth; technological change and resource availability. This means that the methodology is a useful tool for analysing physical assumptions about economic growth, and for understanding how it may evolve in the future.

The second suggested modification to ECCO makes underlying assumptions about the rate of technological progress explicit. The new growth algorithm also allows for capital deepening, by keeping track of the additional capital requirements in a different set of accounts. The models developed do not predict the future; rather, they provide a model for testing various proposed scenarios. From this, specific physical and technological assumptions that are required for the scenario can be identified. Once they have been identified, they can be compared to historical trends and physical laws to see how "realistic" a proposed scenario is.

Slesser's ECCO model is very ambitious in trying to determine the long term growth rate of an economy endogenously and also by attempting to equate embodied energy to economic output. These two factors may perhaps cause some analysts to question the methodology. However, both problems can be overcome and the author believes the resulting methodology is a uniquely powerful tool for understanding critical physical limitations on economic growth.

Notes

1. It should be noted that, in all real multi-good economies, the construction of a price-index is sensitive to the weighting given to each class of goods.

2. The equations are not exactly the same as in the ECCO manual but the key process of growth is however the same. This is because of the unnecessary complexity of the original equations. The differences between these equations and Slesser's are discussed in Appendix 1.

3. This is called the 'fraction not consumed' in the ECCO manuals (Slesser, 1992)

4. The difficulties with this link are explained in more detail with reference to CORECCO in Appendix 1.

5. If one assumes that the same amount of labour is used for each unit of capital, then the quantity of labour available to the new capital will be equal to the labour force times the fraction of capital that is depleted (rate of capital depletion/capital).

6. Currently the fossil energy required to produce electricity (FEREL) in New Zealand is very low due to approximately 80% of electricity being produced from hydro and geothermal sources. One of the scenarios tested in the New Zealand model was that all new electricity is to come from thermal power stations. This naturally increased FEREL to such an extent that it significantly affected the embodied energy in industrial output.

7. Assume for simplicity's sake that it requires no capital to produce the energy.

8. Sufficient model details are not given in the paper to enable one to reach a conclusion about the use of embodied energy as a numeraire.

9. The effect of changing "Output to embodied energy ratio" is the same as changing FEREL in Slesser's models. That is, it changes the quantity of embodied energy required to produce a unit of output. This analysis on changing "output to embodied energy ratio" has been done on actual ECCO models but it is obviously much more complicated than the simple model in Figure 10. The results of the analysis on the ECCO models, however, are the same.

10. See Slesser (1992, p. 57) for details.

Chapter 14: A global systems dynamic model of physical limits

This chapter builds on the previous chapters to produce a simple global model to demonstrate a modelling methodology for analysis of physical limits to growth. Slesser (1992) has produced a similar set of models to illustrate the ECCO methodology. These models are analysed in detail in Appendix 1. The conclusion from this analysis is that Slesser's models need to be significantly modified, to account for the problems with ECCO discussed in the previous chapter.

It is possible to illustrate the basic principles involved with sustainability with a very simple model. These principles are more easily shown in a closed economy than in an open economy that includes imports and exports. The only true closed economy is the global economy, but finding data relevant to the model is difficult and much of the data used in this model may not be very accurate. The main purpose of this model, however, is to demonstrate how physical limits are clarified in an ECCO type model. More effort has been spent on defining the methodology than on finding data. A model with more thoroughly researched data is developed for the New Zealand economy in the next two Chapters.

1 Discussion of CORECCO

CORECCO is a simple world model designed by Slesser (1992) to illustrate the basic concepts of ECCO and how it models physical restrictions on growth of the world economy. It is argued that as resources get used, it takes more capital to make them available to the economy. This means the rate of capital formation in natural capital (RCFNC) increases. At the same time more capital and energy are required in the agriculture (RCFAGR) sector as more has to be produced on each unit of land. These increased capital and energy requirements mean there is less capital available for investment and consumption (CAPINVC) which causes the industrial output to decline after about the year 2000. However, the analysis in Appendix 1 shows that even if the restrictions of agriculture and energy are removed the economy still goes into decline in the future. The reason why industrial output declines when the physical restrictions are removed is related to the way capital is allocated in the model. In CORECCO, growth of population causes an increased demand for consumption goods, which reduces the capital available for investment back into industry (human-made capital). This is the method Slesser uses to "close the loop" and make growth endogenous rather than exogenous[1]. However, it would be difficult to justify this feedback as a physical restriction on economic growth. There are numerous other assumptions one could make about the allocation of industrial output between consumption and investment that would give radically different results. As argued in the previous chapter it is the technological assumptions rather than allocation of industrial output that is important. Results in Appendix 1 show significantly different results with a different capital allocation method.

The main conclusion from this analysis is that the main determinants of growth in the CORECCO model are not the physical restrictions but the method by which capital is allocated within the model. This is another example of the problems with the growth algorithms discussed in the previous chapter. A new series of models is developed that builds on Slesser's CORECCO models, while modifying them to account for difficulties with the growth algorithm and with the use of embodied energy as a numeraire.

2 Sectors in GLOBE

A simple global model is built using the analysis of the previous chapters and the same basic structure as CORECCO. In its simplest form, the model has only an industrial sector and an energy sector. An agriculture and pollution sector are added later, to illustrate how physical restrictions from these sectors may be modelled. A full listing of the models is included on the disk accompanying this thesis (see Appendix 6)

2.1 Industry

The basic growth loop for the industry sector (Figure 14-1) is the same as those in Figure 13-4 and 13-7 in the previous chapter. For simplicity's sake the adjusted capital stock and double set of accounts are not included at this stage. In this model "Other capital requirements" are subtracted from "Industrial output" to leave "Capital available for consumption or investment.[2]" The savings rate is constant, which means a constant fraction is reinvested in industry. The remaining industrial output is available for consumption. In this model the savings rate will determine the rate of growth of industrial output. The associated rate of technological progress is also calculated as a check on the savings rate.

The other new feature is that calculation of industrial output includes energy requirement for energy.

Industrial output = RDC industry + Industrial energy demand*Initial ERE 14-1

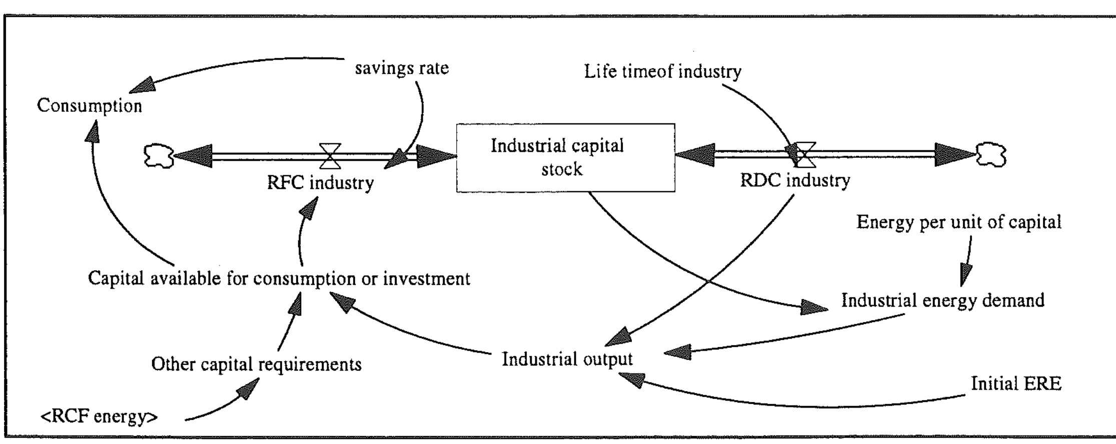

***Figure 14-1** Influence diagram of the industry in a simple global model*

Equation 14-1 calculates the total energy required to produce industrial output. "RDC industry" is the embodied energy required from the capital, "Industrial energy demand" is the "direct energy demand" and "initial ERE" is the energy required to make the energy available. The reason that "Industrial output" is calculated using "initial ERE" is that it is measured in constant embodied energy. The embodied energy set of accounts (EE industrial output etc.) is calculated using the changing ERE (Energy requirement for energy)

2.2 Energy sector

The energy sector has a double set of accounts similar to the industrial sector. One set is measured in constant embodied energy and the other in actual embodied energy (this second set of accounts is not shown to make the diagram in Figure 14-2 easier to follow). The rate of capital formation in this sector is driven by the total energy demand.

Total energy demand = Energy demand for economy * Direct energy required for fuel factor

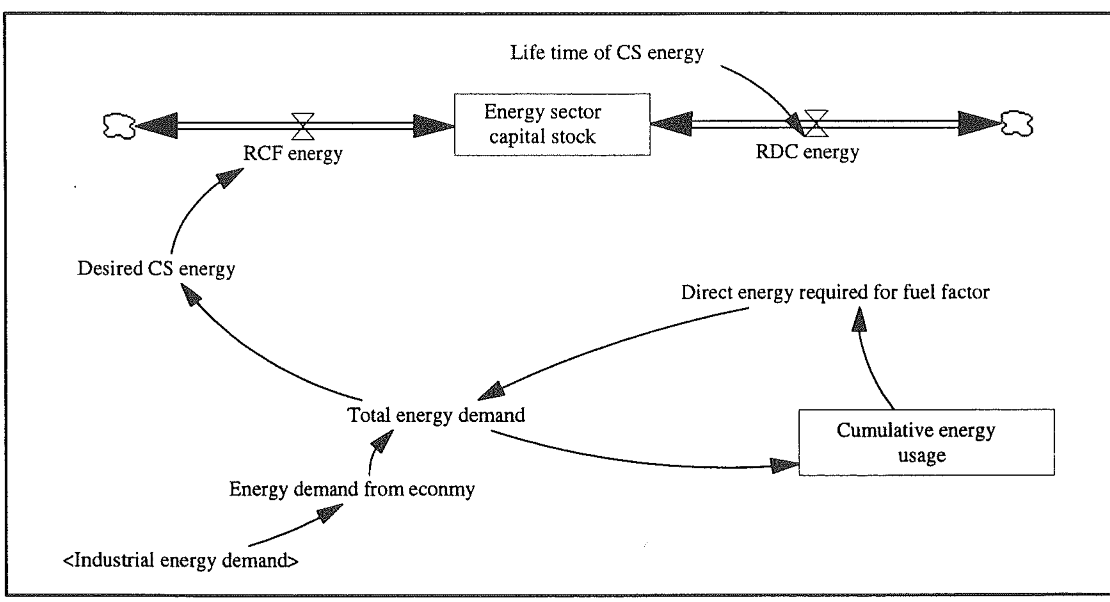

Figure 14-2 Influence diagram of the energy sector in a simple global model.

In this case the only other demand for energy is from industry. The direct energy for fuel factor is the quantity of energy required to deliver one unit of fuel to the economy. A figure of 1.03 means that for every unit of fuel delivered, 0.03 units of fuel are directly consumed in its production. The "total energy required for energy" is the total embodied energy required for energy (EE energy) divided by the total energy supplied. In this simulation the energy requirement for energy is 1.04 which shows that about

0.01 units of indirect energy are required for the production of energy. This is a measure of the energy required to provide the capital etc. The embodied energy set of accounts (EE) is calculated the same way as the industrial sector.

It is assumed that the direct energy requirement for fuel is a function of the cumulative use of energy (see Chapter 11). Figure 14-3 shows how the energy requirement for fuel changes over time. This is done by using a table function in Vensim[3] that relates the direct ERE to the cumulative energy usage. This means that as more energy is used it requires more energy to access it. By the year 2070 the direct ERE is about 1.3 which means that for each unit of energy delivered to the economy 0.3 units are expended. This data is used only to illustrate how increasing energy requirement for energy affects the model[4].

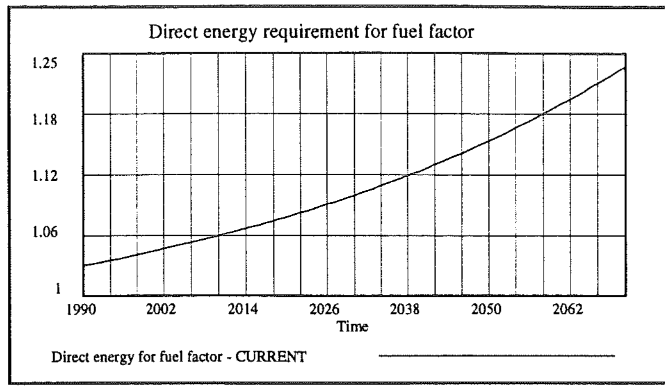

Figure 14-3 *Graph of increasing direct energy requirement for fuel*

The increased ERE increases the total energy demand which in turn increases the capital required in the energy sector. The increased capital requirement in the energy sectors means that there is less industrial output available for consumption and investment. Figure 14-4 shows a comparison to the situation where ERE is constant. The over all effect of this on industrial output is minimal. The reason for this is that the energy sector demands for capital are relatively small compared to industrial output. Even when ERE is rapidly increasing it does not significantly reduce the capital available for investment or consumption.

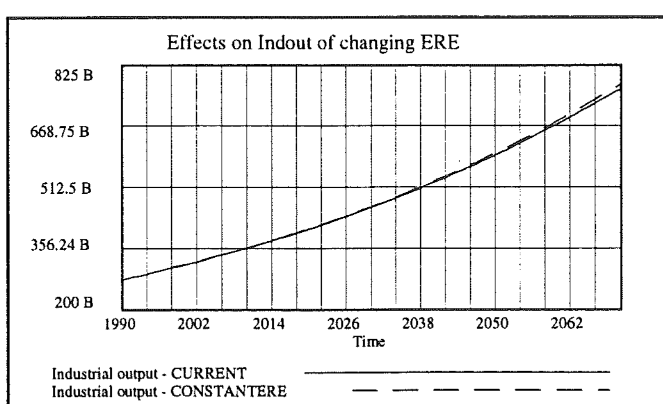

Figure 14-4 *Effect on industrial output of increased energy requirement for energy*

This particular method of simulating increased scarcity of energy resources assumed that the direct energy requirement for fuel was the only factor that changed. In reality the quantity of capital required to make energy available may also increase with cumulative energy use. The following changes are made to the model to include this possibility. The bottom half of Figure 14-5 is not shown, to clarify the adjusted capital

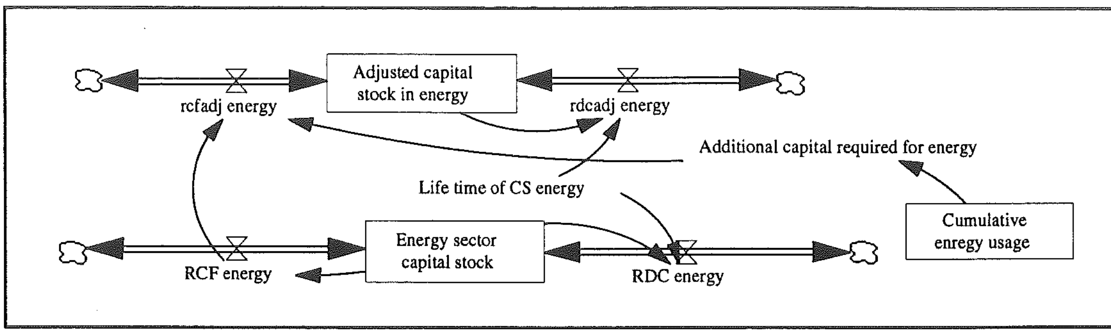

Figure 14-5 *Influence diagram showing how increased capital requirements in the energy sector can be modelled*

stock that has been added to the model. In this case the cumulative energy usage affects the additional capital required to make energy available. The graph in Figure 14-6 shows how the additional capital changes over time[5]. Initially no extra capital is required but by the year 2070 over 1.5 times the current capital of additional capital is required to produce energy. That is, where previously 1 unit of capital was required to produce energy now 2.5 units (1+1.5) are required.

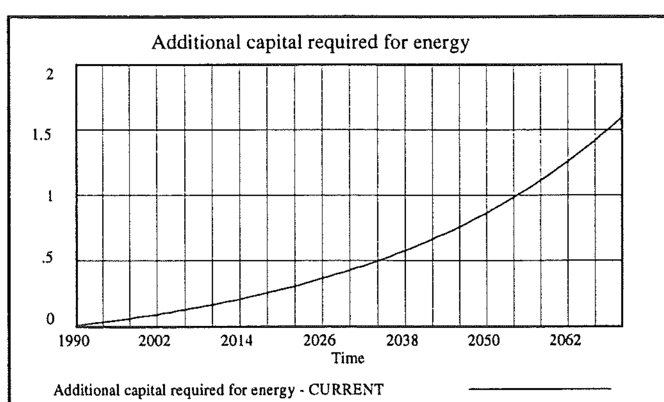

Figure 14-6 *Additional capital required in the energy sector*

The results of this addition to the model are shown in Figures 14-7 and 14-8 Industrial output is reduced due to increased demand for capital and energy in the energy sector (Figure 14-7). This is shown by the fractions of industrial output that are consumed or invested in the energy and industrial sectors (Figure 14-8). The fraction invested in energy is increasing quickly while the fraction consumed and reinvested in industry is reducing.

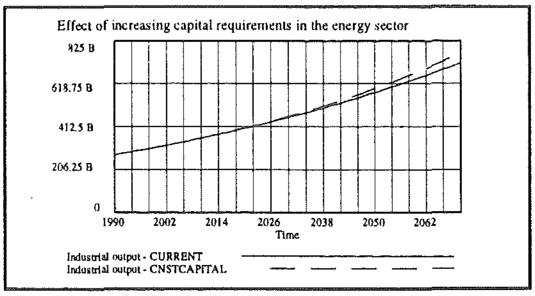

Figure 14-7 *Effect on industrial output of increased capital demands in the energy sector*

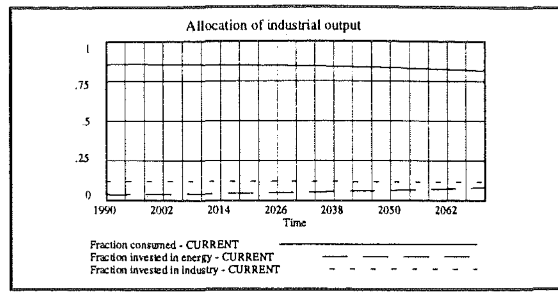

Figure 14-8 *Allocation of capital for an increasing energy sector.*

2.3 Allocation of industrial output

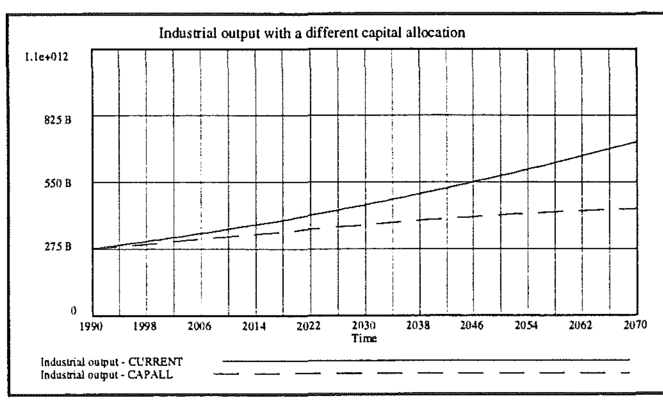

Figure 14-9 *The effect on industrial output of a different algorithm for allocating capital between investment and consumption*

As discussed previously allocation of industrial output is an important determinant of growth in the model. If for example the same physical restrictions are imposed on the economy and the consumption is assumed to be a constant fraction of industrial output then the results of the model change drastically (see figure 14-9). The difference here is that any extra capital required for energy is directly taken off the capital available for investment and consumption. Previously consumption also fell as a result of increased capital requirements so the amount invested did not fall as rapidly.

Each different allocation of capital (choice of savings rate) assumes a different technological improvement rate (average labour productivity increases). The graph in Figure 14-10 shows the assumed increase in labour productivity for the different capital allocation methods. The low growth rate scenario (capital) assumes the rate of technological progress is slower that the previous method of capital allocation[6]. As emphasised in Chapter 9 these technological factors may be the important limits so it is important that they are calculated for each simulation.

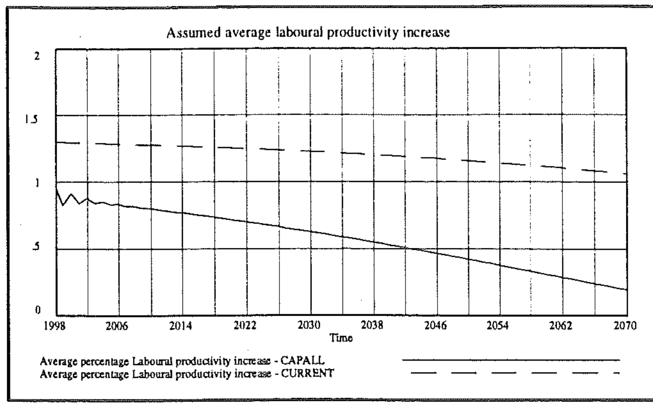

Figure 14-10 *The assumed rate of labour productivity for different methods of allocating capital between investment and consumption*

One of the biggest difficulties with a model like ECCO is determining a realistic growth scenario based on decisions between investment and consumption. The graphs in Appendix 1 show that it is a major determinant of the overall growth of the model yet there is no sure way to know how industrial output is allocated between investment and consumption. Slesser has developed a method of allocating capital that makes the growth of the model endogenous (see Appendix 1 and the previous chapter for details). However, it is difficult to justify any set method of determining savings rate when one considers the complex forces that influence it.

Economists are not exactly sure what causes changes in the rate of savings: Samuelson and Nordhaus comment on the enigma of changing saving rate in the US economy: "The declining national saving rate remains a puzzling phenomenon testing the ingenuity of macro-economists (Samuelson and Nordhaus, 1989, p. 144)." Some factors that contribute to savings rate are federal budget deficits, social security system, attitudes towards debt and changes in taxing policy[7]. Over the time period of ECCO models it is next to impossible to estimate how these economic factors might change. The point of this discussion is to show that there is no easy way to determine the savings rate and any attempt to endogenously determine the savings rate will be questionable[8]. Therefore, the savings rate should be stated explicitly as a simulation variable. The simulation should also include a calculation of the assumed technological improvement to see if this is realistic based on historical trends.

Some interesting data on the changing savings rate in the US economy is that between 1950 and 1970 the saving rate fluctuated around an average of 8% of net national product (NNP). Since then it has fallen significantly to as low as 2% of NNP (Samuelson and Nordhaus, 1989, p. 143). The physical model developed in this thesis offers a possible physical explanation for the decreasing savings rate in the USA. If it is becoming more difficult to achieve technological improvement then investments (savings) will not bring the same return on investment (it is only technological improvement that brings economic growth and hence returns on investment). It is not worth saving when this saving does not result in a significant technology improvement (and hence return on investment) so savings remain low. Even in Japan where savings rates remain high the growth rate of their economy has slowed considerably. It is not possible to say whether low investment causes a low rate of technological change or low potential for technological change causes a low investment rate.

Although growth rates in this model are exogenous the model structure is flexible enough that a number of different methods of making growth endogenous are possible. Future ECCO type models could include prices and elasticities to predict changes in human behaviour and hence growth rates. Any endogenous growth algorithm must be consistent with the structural information and physical flows already included in the model.

3 Agriculture sector

As identified in Chapter 7 the agriculture sector is a key interface between the economy and the environment. The relative size of this sector will be one indicator of the importance of the environment. A dynamic systems diagram of the important influences is shown in Figure 14-12. The size of the agriculture sector is driven by the population and the food demand per person. From this the total food demand and capital stock required to produce this food can be calculated. Physical limits are modelled by calculating how much food needs to be produced per unit of land. As this increases, the energy required to produce a unit of food will increase, and hence this efficiency factor

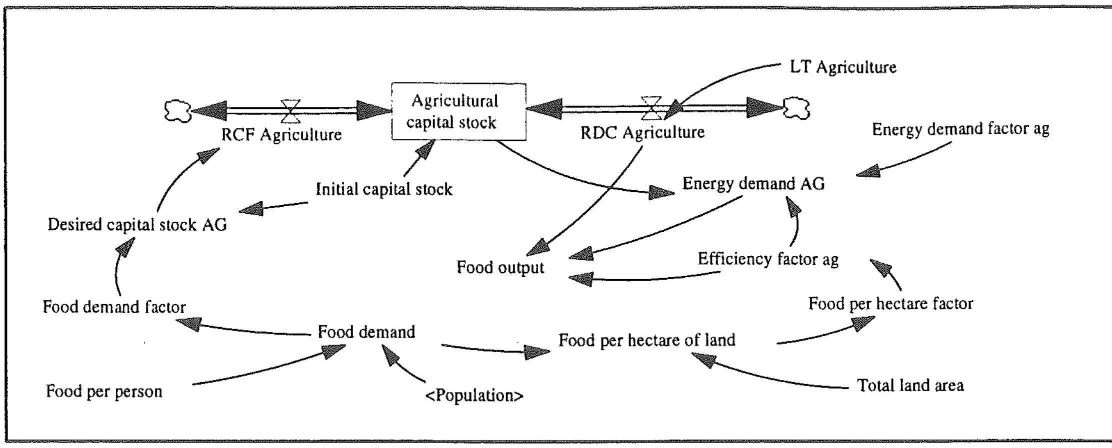

Figure 14-11 Influence diagram of a simple agriculture (ag) sector

will affect the energy demand per unit of capital stock. As in the energy and industry sectors, the main set of accounts is measured in constant embodied energy while the embodied energy in agricultural output (EE Ag) is a measure of the real embodied energy required to produce the output. The graph in Figure 14-13 shows a comparison of the two outputs. This indicates that agricultural output is becoming increasingly physically difficult. There may also be an increasing demand for capital due to the increased intensity of food production but this is not shown in this model for simplicity. It is also possible for pollution to affect agricultural output. This is just one example of how physical limits may be modelled in the agriculture sector.

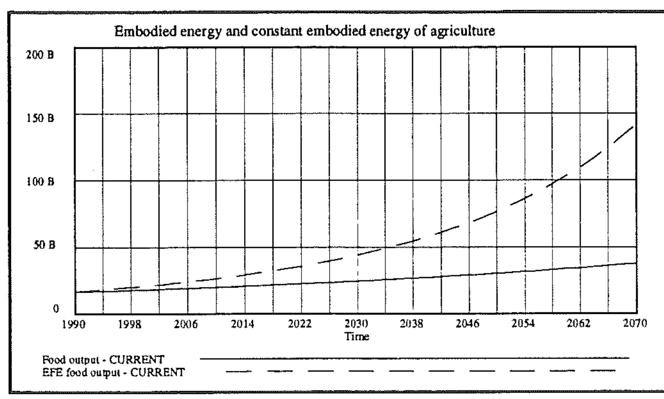

Figure 14-12 Comparison of the actual embodied energy and constant embodied energy of agricultural output in a simple global model

4 Pollution sector

There needs to be a pollution feedback to model the negative affect on the environment of continued waste output from the economy. The level of pollution in the biosphere is the important factor, rather than just the rate of pollution formation. A comprehensive model would calculate the level of a number of different pollutants both globally and regionally. Examples could include greenhouse gas emissions, ozone depleting substances, solid wastes etc. The feedbacks of each of these pollutants can then be included in the different sectors depending on their effects. This simple model has only one level of pollution to demonstrate the calculations involved (Figure 14-13).

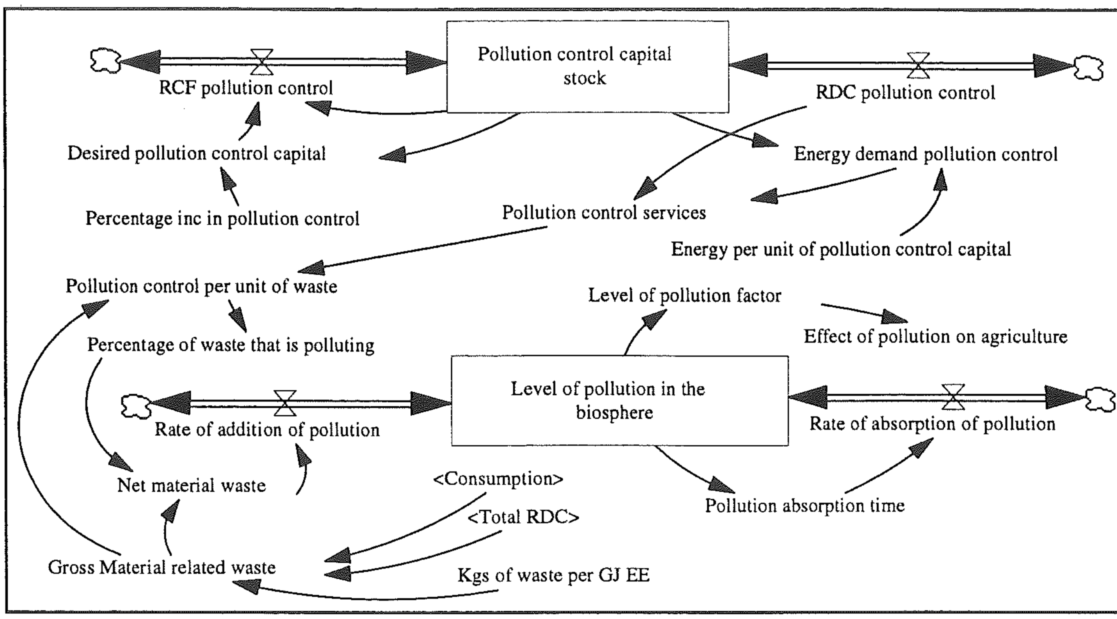

***Figure 14-13** Influence diagram of the pollution sector in a global model*

In this simple model the pollution control service only reduces the amount of waste that is added to the existing pollution. A more comprehensive model might include the possibility of pollution control services removing already existing pollution. The Gross Material waste is assumed to be proportional to the rate of capital depletion and consumption. All discarded capital and consumption will be waste of some kind. From this the total quantity of waste can be estimated. Of this gross waste only a fraction will be polluting[9] and this net material waste is the rate at which pollution is added to the biosphere. The level of pollution in the biosphere depends on the rate at which the pollution is being absorbed and this in turn may be affected by the total level of pollution[10]. It is difficult to estimate these parameters for an aggregated pollution sector but it is easier if the types of pollution are split up. The aim of this model is to show how the interconnected physical flows can be modelled.

It may be a policy decision to invest in pollution control. In this example the level of pollution control changes the percentage of waste that is polluting. If, for example, there is a large level of pollution control, then less of the net waste will be polluting.

The level of pollution in the biosphere can affect a number of model variables such as the yield of agricultural products and the health of the population. Initially, for simplification only, the effects on agricultural production will be modelled. The way in which pollution is assumed to affect agriculture is to decrease the total land available for production. There are many other ways this feedback could be included, such as decreasing the output per unit of land. The method chosen here is used to demonstrate one example of how a pollution feed back may be modelled. Figure 14-14 shows how the available land decreases as pollution increases over time[11]. This in turn will affect energy requirements in the agriculture sector, which decreases the capital available for consumption or investment.

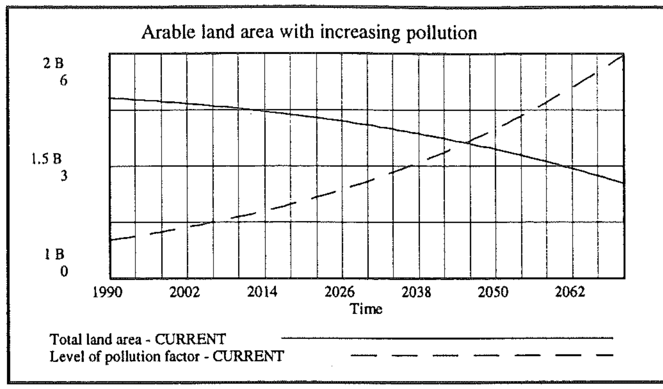

Figure 14-14 *A possible feedback of increasing pollution is decreasing arable land availability*

Another limit on pollution may be modelled by having an exogenously determined acceptable pollution level in the biosphere[12]. This may trigger a policy decision to increase investment in pollution control. The graph in Figure 14-15 shows how the pollution control system may limit the quantity of new pollution into the biosphere.

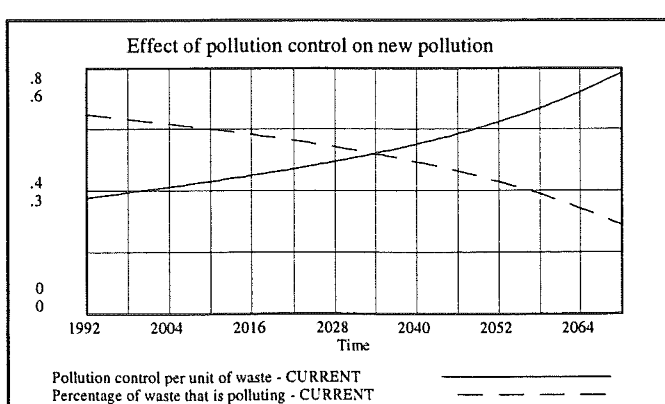

Figure 14-15 *The possible effect on new pollution of pollution control technology*

There are many complicating factors involved in the modelling of pollution such as synergetic effects, thresholds, feedbacks and delays (see Chapter 11). The dynamic simulation modelling environment is ideal for modelling such complexities. As always, the model will be limited by the knowledge of the system being modelled. The modelling process forces one to be explicit with the assumptions so they are open to scrutiny and debate.

5 Indicators from a simple global model

Because the data for the global model are questionable it does not make sense to draw conclusions about the world economy from this model. The point of this model is to illustrate the methodology. The following indicators illustrate the type of information about physical limits that are possible from this type of model.

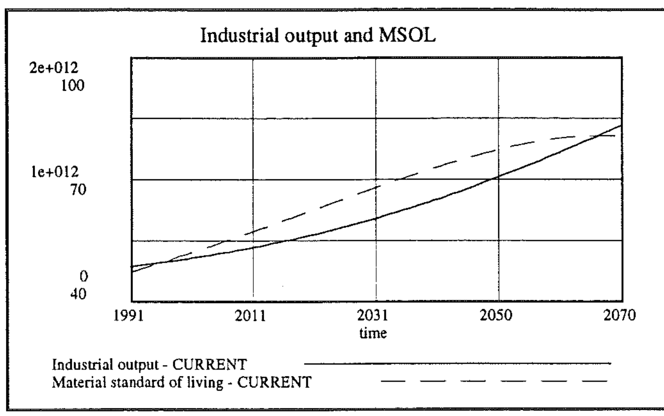

Figure 14-16 *Two important indicators in the model: Industrial output and material standard of living*

Overall indicators include material standard of living and industrial output. In the example in Figure 14-16 industrial output continues to increase but material standard of living starts to level off due to the population increasing at a faster rate than industrial output.

5.1 Allocation of investment

An indicator of sustainable development from this simple model is the fraction of investment in different sectors of the economy. If the fraction of investment in the environmental sectors is small and not increasing then this indicates that physical limits are relatively insignificant. If, however, the size of these systems within the economy is increasing then this will indicate that physical limits are becoming significant. This will restrict economic growth because of the extra requirements for capital labour and energy.

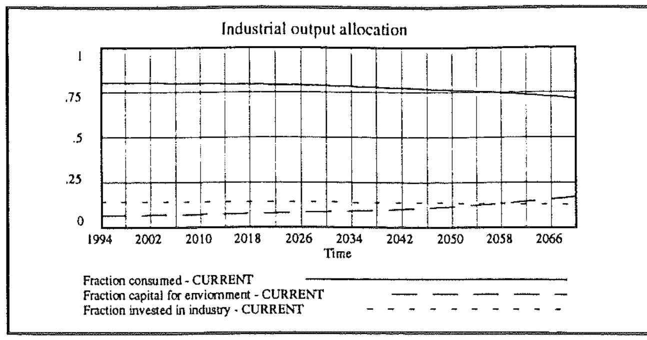

Figure 14-17 *Allocation of capital between consumption industry and the environment*

Another possible indicator of the physical difficulty of achieving growth will be the fraction of total output that is reinvested or saved. If the savings rate is low this indicates that it only requires a small investment to achieve the desired growth rate. If the savings rate is high then this shows that it is more difficult to achieve growth.

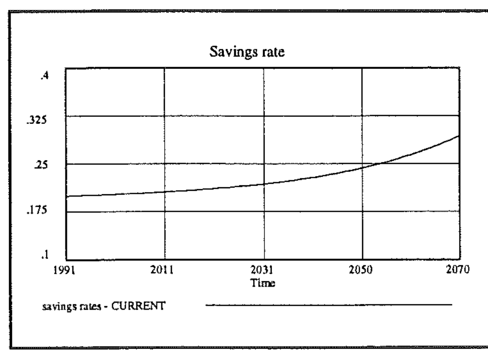

Figure 14-18 *Fraction of total industrial output that is invested rather than consumed*

5.2 Embodied energy indicators

Embodied energy is a measure of the physical difficulty of achieving a task. If this is increasing then this indicates that tasks are becoming more physically difficult to achieve. In other words, it shows that increases in energy requirements, due to environmental factors, dominate decreases in energy demands caused by technological improvement.

The model shows that, even though the direct energy required to provide consumption goods may be constant, the total embodied energy is increasing. This means that it is becoming more physically difficult to provide a unit of consumption. This information is not as readily available from other economic models. If the assumed relationship between energy use and technology holds, then this may also indicate which sectors in the economy are more likely to grow. The embodied energy analysis also makes it possible to determine the precise quantity of carbon dioxide emitted from each sector in the economy. This may aid policy analysts in determining the effects of various other methods of controlling carbon dioxide output.

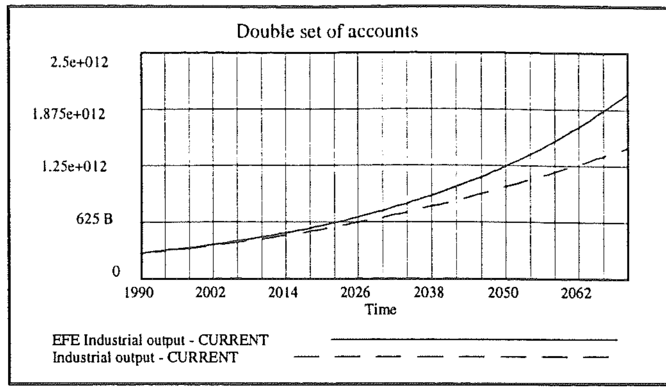

Figure 14-19 *Comparison of constant embodied energy and actual embodied energy of industrial output,*

The total quantity of energy used by the main economy and the environmental sectors (energy, agriculture and pollution control) is another indicator of sustainability. The graph in Figure 14-20 shows that more physical effort is required to run the environmental sectors of the economy.

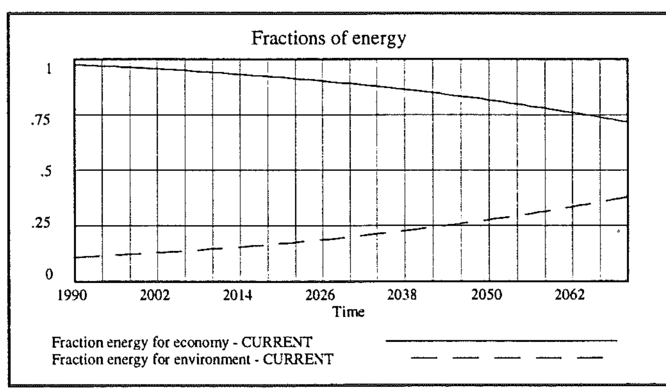

Figure 14-20 *Fraction of energy used in the main economy and in environmental services*

6 Critical determinants of growth in the global model

One cannot expect a model to give insights into all aspects of sustainability. The aim of the model used here is to understand some physical influences and assumptions underlying economic growth. For any particular exogenous growth scenario, the modeller must make explicit assumptions about the capital and energy requirement in the environmental sectors. Assumptions about pollution output and feedbacks must also be explicit. From this, the model simulates the growth and calculates the assumed rates of technological improvement in each sector. These rates of growth can be compared to historical rates to see how probable they are. If they are unrealistic, a new simulation with a different allocation of capital should be used. Indicators from this type of model are discussed more fully in relation to the New Zealand model in Chapter 16.

Physical limits on economic growth occur because the sectors of the economy interacting with the environment require larger inputs of capital, labour and energy. If this occurs, capital is not available for consumption and investment thus reducing the growth of the economy. The other important feature is how labour productivity (technology) changes. As each sector grows assumptions about the rate of growth of labour productivity must also be made. The discussion on technology in Chapter 10 shows that this may be a significant limiting factor on long term economic growth.

The key physical restrictions in this Globe model are given by the following factors

-Energy and capital requirements for energy

-Energy and capital requirements for agriculture

-Energy and capital requirements for pollution

-The effect of pollution on agriculture

-Acceptable level of pollution

Additional assumptions of the model include the following:

-Land is used for agriculture only[13]

-The only pollution feedback is to reduce the total arable land available

-Technological progress rates are achievable

-Increased agricultural yields are achievable[14]

-Pollution reducing techniques are available at the capital requirements stated.

Each of these quite specific assumptions is explicitly stated in the model and can be changed to see the effects of different assumptions. The reason for using embodied energy in the model is that it is believed that this may give important information about these physical assumptions.

Although the physical parameters used in the global model are reasonably pessimistic the overall effect on the growth of output and material standard of living is surprisingly small compared to results of other similar models. The reason why Slesser's models appear more pessimistic seems to lie in his assumptions about allocation of capital and the use of embodied energy as a numeraire. The "Limits to Growth Model" results are more pessimistic because of the Malthusian assumptions about resources and the assumptions about the negative feedbacks of pollution. If these stronger pollution feedbacks are included then the model will give broadly similar results.

The level of aggregation in ECCO needs to be such that those critical physical factors that determine growth are easy to estimate. In the global model presented here, the sectors are too aggregated for it to be possible to find realistic data. The simulations demonstrate how each of the limits is included in the model, but the data are such that it is not possible to draw firm conclusions. In the following chapter, a model of the New Zealand economy is developed with a more detailed level of aggregation that make finding and estimating data easier.

7 Summary

A review of Slesser's CORECCO series of models showed that the main determinant of growth was the almost arbitrary method of allocating industrial output between investment and consumption. A new global model has been developed to clarify the key issues of sustainability and demonstrate how they might be modelled. The capital and energy requirements of the agriculture, pollution and energy sectors ultimately determine how much capital is available for investment and consumption. Assumptions about the effects of pollution also have a significant effect of the outcome of the model. The strength of ECCO is that the tables that are the key to how the global economy will grow are in physical units and these tables can be based on physical trends. The process of building the model forces one to make assumptions about physical flows explicit, so they can then be open to scrutiny. Changes can easily be made and a new simulation will show the relative importance of different variables.

Notes

1. Slesser does note that his method is not the only method of closing the loop, however, it is not made clear what a huge significance this feedback has on the model or how uncertain this feedback is.

2. A number of the influence diagrams in this chapter do not show all of the influences. For simplicity's sake only the most important influences are shown. A full model listing can be found on the disk accompanying this thesis (see Appendix 6).

3. Vensim is a dynamic simulation software package. The table functions in Vensim are called "lookup" functions.

4. This scenario is based on the assumptions of Slesser (1992) that the energy required to access energy will increase in the future. This data needs more investigation before one could have confidence in it.

5. The additional capital is actually a function of cumulative depletion.

6. Yet a different capital allocation method may assume that consumption drops allowing high investment. In this case the assumed percentage increase in labour productivity may rise over time.

7. As discussed in Chapter 4 one of the aims of econometric models is to estimate short term growth rates based on these factors.

8. This is particularly true for long term models. Short term econometric models have some success at endogenously determining savings rates and hence growth rates.

9. See Chapter 7 for a definition of polluting.

10. This assumption has been made in other world models (Meadow et al. 1972, Forrester, 1971) and is a key reason for the high rate of increase in the level of pollution in these models.

11. It should be noted that in this scenario pollution is related to the depletion of capital and to consumption rather than energy. If the level of pollution was related to energy it would increase at a much faster rate.

12. This level of pollution may come from a scientific consensus on the safe level of pollution before there is risk of a collapse of critical biosphere functions.

13. Significant land areas will also be required for human settlement and possibly renewable energy technologies.

14. As indicated in Chapter 11 this is a particularly questionable assumption.

Chapter 15: Description of a dynamic simulation model of the New Zealand economy

The previous chapters have discussed the theory and methodology behind a physical model to indicate possible physical limits to economic growth. This chapter shows how this theory can be applied to a national economy. A number of new concepts such as input-output analysis, imports and exports need to be discussed. Different methods of verifying the New Zealand model and some simulation options are also investigated. Different scenarios and results of the model are presented in the next chapter.

1 Scope and purpose of the New Zealand model

The previous chapter emphasised the significant changes in methodology from earlier ECCO models. The model discussed here has more appropriately been called a Structural Economy-Environment Simulation Models (SEESM) simulation model of New Zealand. Figure 15-1 is a diagram that shows the information structure of NZSEESM.

The initial conditions required for the model include capital stocks, resource demands and structural information. The structural information states where the inputs and outputs from the various sectors of the economy go. This is found from standard economic input-output tables. The scenario options that can be changed include the fuel efficiencies, capital requirements, pollution assumptions and growth rates.

From these initial conditions and scenario options the model calculates the outputs of each sector of the economy, the change in input-output structure, the resource demands as well as technology and pollution information. The power of the dynamic simulation

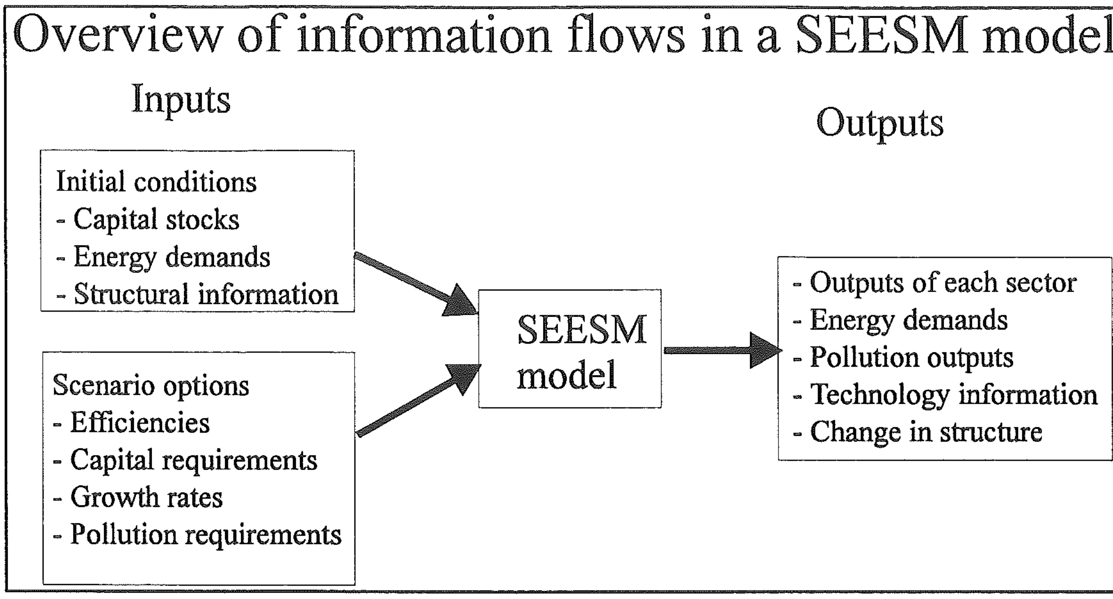

Figure 15-1 *Information inputs and simulations outputs from the New Zealand SEESM model*

model is that changes in assumptions and causal links can easily be made to test any imaginable scenario. Because of the numerical technique used for the simulation, links between variable and exogenous data can be nonlinear. It is easy to change a scenario to gauge the significance of different parameters and policies.

Because NZSEESM includes detailed data on the structure of the economy it can give a quantitative estimate of the effects of different scenarios. With the level of detail in the NZSEESM series of models, specific growth scenarios can be simulated. For example, what would be the effect of a 5% annual increase in exports from the Industry sector? This would cause an increase in all inputs to Industry, which in turn would increase the energy demands and inputs to those sectors. This may trigger other feedbacks relating to pollution and capital demands. This assumption will also change the balance of payments. The physical (resource and pollution) consequences of all these interactions can be accounted for in NZSEESM.

It should be stressed again that the model cannot predict growth rates, changes in efficiency and capital requirements. These must all be set exogenously and the model then calculates the physical flows and change in structure that result from these exogenous variables. In this way NZSEESM is not an optimisation model; it is a simulation or "what if?" model.

2 Methodological issues in a national economy

The following section discusses several new methodological problems relating to modelling a national economy. These problems relate to choosing the appropriate level of aggregation, the use of input-output analysis and the modelling of external flows such as imports, exports and international debt.

2.1 Level of aggregation in the model

As with all models there is a delicate balance between the complexity and manageability of the model. If the model has too many sectors and feedbacks it is extraordinarily difficult to understand and gain useful information from it. Yet if the model is too aggregated it may be too simple to understand the essence of the problem. The New Zealand model described in this chapter (NZSEESM) is split into six sectors: Industry, Services, Transport, Life support, Electricity and Thermal fuels. Earlier models constructed by the author had significantly more sectors. It was found that these models became hopelessly complex and it was particularly difficult to communicate the reasoning behind the model[1]. Although NZSEESM has only six sectors there are a surprising number of scenarios that can be tested and some significant results have been found (see the following Chapter).

Though NZSEESM is split into only six sectors the critical factors in each of these sectors can be split further to get more detail. For example the transport sector can be split into any of the following sub sectors:

Type of transport	- Passenger
	- Freight
Method of transport	- Air
	- Sea
	-Land -Rail

-Road - Public

- Private

If each of these sectors were modelled separately, it would vastly increase the complexity of the model. Many input-output data sets are not aggregated to this level anyway. However, an understanding of the subsectors within transport can be included in the six sectors New Zealand model. For example, a scenario of increased public transport may be tested by linking energy demand in the transport sector to the fraction of transport that is provided by public transport. This type of modelling allows more complicated scenarios yet it keeps the model manageable.

2.2 Input-output analysis

Input-output data are used to find the initial conditions and structure of the model.[2] This input-output data gives a detailed snapshot of all the transactions between sectors in the economy. The transactions are measured in financial terms but can be transformed into energy flows (Peet, 1993). Table 15-1 shows thermal fuels measured in PJ/y, electricity measured in GWh/y, and the other inter sector transactions as a percentage of total ($) output in the New Zealand economy in 1981-82.

	Thermal fuels	Electricity	Agriculture	Industry	Transport	Services	Households	Exports	Gross capital formation	Total
Thermal fuels	66	29	15	65	31	29	72	16	0	323
Electricity	58	2858	522	7720	262	3277	8265	0	0	22962
Agr	0.01	0.01	20.27	57.50	0.19	2.16	9.34	10.42	0.09	100
Industry	0.25	0.07	5.88	34.20	1.76	9.02	15.86	17.72	15.23	100
Transport	0.46	0.09	6.24	23.07	10.41	13.36	16.09	30.05	0.23	100
Services	0.23	0.14	3.18	14.52	2.00	16.72	54.55	5.28	3.39	100
Imports	9.33	0.03	3.88	33.35	3.81	9.23	25.57	2.56	12.23	100

Table 15-1 Input-output transactions matrix used for the NZSEESM model

Some examples of the information from the table are:

- Thermal fuels to Industry (TF2IND) = 65 PJ/y
- Electricity to Industry (EL2IND) = 7720 GWh/y
- Transport to Industry (TR2IND) = 23.07 % of total transport sector output.
- Services to households (SR2DOM) = 54.55 % of total services output

A full explanation of the input output data and assumptions is in Appendix 2. From the input-output data the energy intensities of each sector in the economy can be found using standard matrix methods to solve the simultaneous equations. The use of input-output and related data (eg on capital stocks) ensures the SEESM model has very accurate information of the physical structure and the flows within the economy.

2.3 Calculating embodied energy in SEESM models

Outputs in each sector of the economy are measured by the total amount of embodied energy required to make that economic activity possible. All inputs to the sector need to be considered when calculating the output. The direct energy inputs are measured in GJ, for thermal energy, and kWh, for electricity. These direct energy inputs are multiplied by factors to include the indirect energy required to produce that energy. All other inputs are measured in embodied energy. For example:

INDOUT = RDCIND + TEDIND*SYSGER + EEDIND*FEREL + TR2IND[3]

INDOUT	Embodied energy in industrial output GJ
RDCIND	Embodied energy in the rate of capital depletion GJ
TEDIND	Thermal energy demand GJ
SYSGER	System gross energy requirement GJ/GJ
EEDIND	Electricity demand in industry kWh
FEREL	Fossil energy requirement for electricity GJ/kWh
TR2IND	Transport to industry GJ

TR2IND=TRAOUT*FTR2IND

TRAOUT	Transport output GJ

FTR2IND Fraction of transport to industry

All the inputs to industry are summed to calculate the total embodied energy required to produce industrial output. The embodied energy of each sector is calculated this way and this creates a set of simultaneous equations. A method of solving a series of simultaneous finite difference equations is outlined in Appendix 3.

2.4 Growth algorithm

The main conclusion from the discussion on growth in Chapters 9 and 10 is that it is impossible to *predict* long term growth in an economy. For this reason growth in NZSEESM is determined exogenously as a simulation variable. There are two significantly different ways growth can be simulated.

-Exogenously state growth rates and have the model calculate the implied change in labour productivity (technological change) or

-Exogenously state changes in labour productivity and have the model calculate growth rates in the different sectors.

In each of these cases, changes in assumptions about imports and exports will affect growth of the economy. For example, demand for extra capital from the industrial sector could be supplied by imported capital. This will alter the energy demand within the economy. In NZSEESM growth rates are stated exogenously and the model calculates the assumed change in labour productivity.

The critical determinants of growth in NZSEESM are the growth rates to final demand and export of each sector in the economy. All of the internal flows required to make this growth scenario happen are automatically calculated (see Appendix 5 for details). For example, a growth scenario may have exports from the agriculture sector growing at 4%. Inputs to the agriculture sector such as transport and industrial output must grow to adjust for this.

In Slesser's ECCO models, the growth rate is determined by the capital available for investment. In the SEESM model, if the total rate of capital formation required in the scenario is greater than the capital available for investment, then capital is imported. This is commonly how a real economy would work. Another option is to increase the current rate of investment in the industrial sector, so that there is more capital available in the future. Again this is an option for the simulation.

2.5 Imports, exports and debt assumptions

The model may be used to simulate these external factors to gauge the influence they may have on physical flows in the economy. Initial rates of imports and exports for the different sectors in the economy are found from the input-output tables. The default setting for imports is to have them growing at the same rate as the sector they are supplying.

These growth rates can easily be changed by the modeller. The assumed embodied energy of these imported products can also be changed. The default setting is the average energy intensity of the New Zealand economy. The growth rates of exports from each sector of the economy are exogenous variables of each particular scenario and can be set separately for each sector of the economy.

There is a simple algorithm in the model to calculate overseas debt, based on the current debt, assumed future interest rates and the balance between imports and exports. The exogenous rates of export and assumptions about imports will determine the future level of debt. It is also possible to set the model up so that if debt reaches a certain level then imports will reduce or exports will increase.

3 Description of the New Zealand model structure

The following section briefly describes the way the New Zealand model is divided, the data and scenario options along with a brief description of the key algorithms in the model.

3.1 Sectors within the New Zealand economy

The diagram in Figure 15-2 is an extension of those developed in Chapter 7 and it shows the different sectors in the New Zealand model. The main economy includes industry, services, transport and households. The sectors that interact with the environment are split into thermal fuels, electricity and life support (agriculture and forestry). Appendix 4 gives the input-output sector break down in greater detail. Imports and exports are the external flows to and from the international economy. The feedback from Net Pollution to Resources is also shown although there is at present no specific pollution control sector in NZSEESM[4].

3.2 Data requirements for the model

This example from the transport sector shows the initial conditions required for each

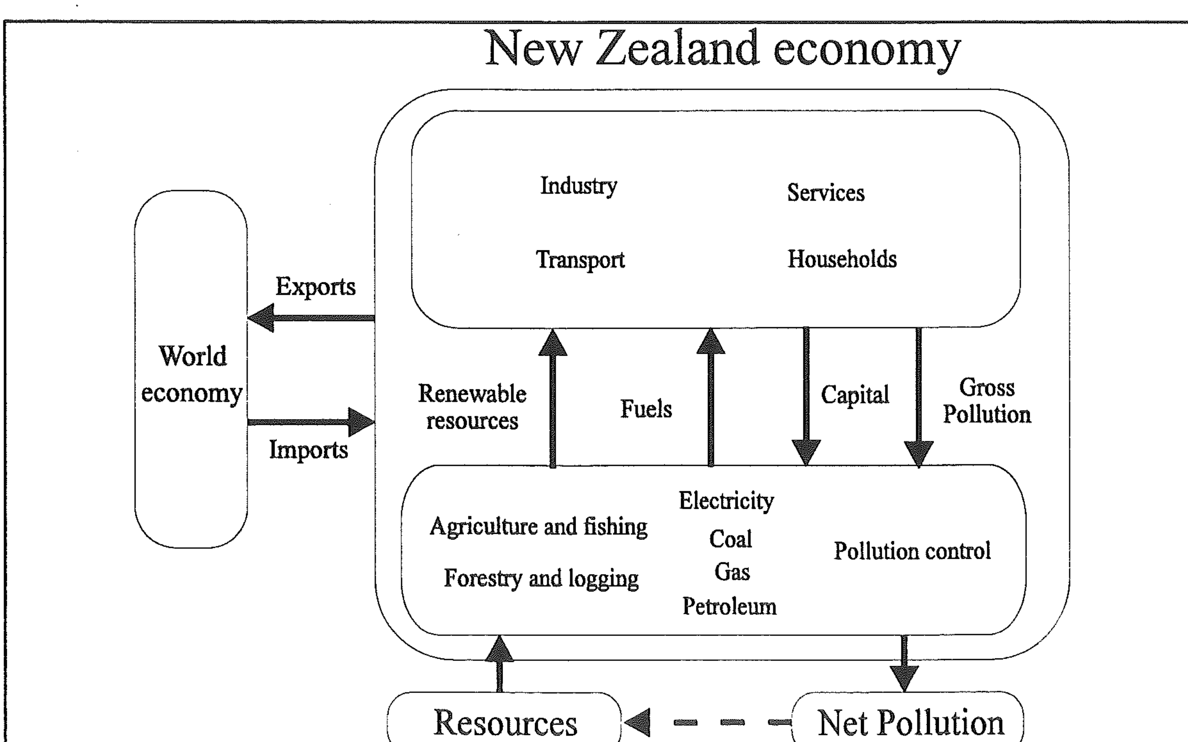

Figure 15-2 Sectors and critical flows in the New Zealand SEESM model

sector in the economy. Details on the data sources used in NZSEESM are given in Appendix 4.

Initial conditions:

N NCSTRA=8.416E9	Initial capital stock - transport ($ 82)
N DTRA=0.5	Delay in construction - transport (yr)
N LTTRA=19	Life time of capital stock - transport (yr)
N TRATED=3.1168E7	Thermal energy demand - transport (GJ/yr)
N TRAEED=2.61659e7	Electricity demand - transport (kWh/yr)
N NTRAOUT=71.640E6	Initial transport output (GJ)
N TRAOUT$=3.294374300e9	Initial transport output ($)
N NLABTRA=75600	Initial labour input - transport (L)

N NTR2PRF=0.1609	Fraction of transport to final demand
N NTR2SRF=0.1336	Fraction of transport to services
N NTR2INF=0.2307	Fraction of transport to industry
N NTR2TRF=0.1041	Fraction of transport to transport
N NTR2TFF=0.0046	Fraction of transport to thermal energy
N NTR2ELF=0.0009	Fraction of transport to electricity
N NTR2LSF=0.0624	Fraction of transport to life support
N NTR2EXF=0.3005	Fraction of transport to export
N NTR2GCF=0.0023	Fraction of transport to GFCF

This last section of data is from input-output tables and shows where transport goes within the economy. The transport to final demand fraction (NTR2PRF) is 0.1609 so 16.09% of the total transport output goes direct to final demand. In the UK ECCO model (Slesser et al., 1994) transport goes to either industry or final demand and it is assumed no other sectors require a transport input (see table 2 in Appendix 2). The input-output information in the New Zealand economy shows that many sectors within the economy require transport services. It is important to include this data if one simulates a scenario where different sectors grow at different rates.

3.3 Exogenous scenario information required

The following list shows the information required to specify a particular scenario. The energy demands are changed by altering the efficiencies[5]. The other important variable is the quantity of additional capital required to achieve the improved efficiency. This is stated as a fraction of the rate of capital formation in that sector. In the example below the efficiency and capital factors are set to a general efficiency factor defined elsewhere in the program (see Appendix 5 for details).

Future conditions:

A EFTHTRA.K=GENTEFF.K	Thermal energy efficiency of transport
A EFELTRA.K=GENEEFF.K	Electricity efficiency of transport

A RFTHTRA.K=RCFTRA.KL*GENCPTH.K	Extra capital required for thermal efficiency
A RFELTRA.K=RCFTRA.KL*GENCPEL.K	Extra capital required for electric efficiency

GENTEFF.K=General thermal fuel efficiency
GENEEFF.K=General electricity efficiency
RCFTRA.KL=Rate of capital formation in the transport sector
GENCPTH.K=General capital required to improve thermal fuel efficiency
GENCPEL.K=General capital required to improve electricity fuel efficiency

Desired growth rates

A GRTR2PR.K=0.02 (2%)	Growth rate of transport to final demand
A GRTR2SR.K=GRSER.K	Growth rate of transport to services
A GRTR2ND.K=GRIND.K	Growth rate of transport to industry
A GRTR2TR.K=GRTRA.K	Growth rate of transport to transport
A GRTR2TF.K=GRTFX.K	Growth rate of transport to thermal fuels
A GRTR2EL.K=GREL.K	Growth rate of transport to electricity

A GRTR2LS.K=GRLS.K Growth rate of transport to life support

A GRTR2EX.K=0.03 (2%) Growth rate of transport to exports

A GRTR2GC.K=GRPER.K Growth rate of transport to gross capital formation

The other information required for each scenario is the growth rate of transport. In this model the growth rate of transport to each sector. Only growth rates to final demand and export need to be specified. In this example it is assumed that the rate of growth of transport to final demand is 2% and to export is 3%. A more realistic growth rate to final demand may be some function of the growth rate of the population and the material standard of living. The growth rates of transport to the other sectors are assumed to be proportional to the growth rate of that sector. For example, the growth rate of transport to services is assumed to be the same as the growth rate of services. If the modeller has information to suggest that the rate of growth of transport to services will be different this can also be included. A scenario may be that transport may only require half the amount of services input so the case the following equation could be used:

GRTR2SR = 0.5*GRSER

GRTR2SR = Growth rate of transport to services

GRSER = Growth rate of services

3.4 Explanation of the model algorithms

Given the initial conditions and the scenario variables there are a number of calculations that are common to each sector of the economy. There are nine key algorithms that form the basis of the NZSEESM model and the purpose of each is briefly described below. A more detailed explanation of these algorithms (macros) and a partial program listing is given in Appendix 5.

The first three macros calculate the capital stocks within the sector. The capital stocks are measured in constant embodied energy and embodied fossil energy. The additional or adjusted capital stock is also calculated[6]. The next three macros calculate the embodied energy of the output including all direct and indirect energy flows. Again the outputs are measured in embodied energy and constant embodied energy. The next macro uses the input-output information (fraction of output to each sector) and the desired growth rate of each sector to calculate the new input-output information. This information is then used to calculate the allocation of output to each sector in the economy. The last two macros calculate the growth rate and labour productivity of the sector.

4 Validation of the model

Any discussion on the validity of a model only makes sense with respect to the purpose of the model (Bossel, 1994, p.85). Here the purpose of the model is to investigate possible long term physical limits to the growth of the New Zealand economy. The model does not predict but investigates the relative effects of different policy changes and the associated physical assumptions. The model is not designed to show short term fluctuations in growth.

Part of the validation of the model involves simulation of scenarios to see if the outcome makes sense. If it does not then the model can be investigated to see why. If the model can be used to explain the effect then something new will have been learned about the system (see the following Chapter). Quite often, counter intuitive behaviour will be caused by a mistake in the model. Investigation of the ECCO methodology in Chapter 13 was instigated because the models were not giving sensible results. The result is that the methodology has been altered so the behaviour of the model can be justified.

Given that it is very easy to make mistakes in large simulation models, two methods of checking for errors have been developed. These checks involve (1) the use of an energy balance and (2) static input-output data analysis. An empirical validity test is also discussed. It should be emphasised that there is no test that can truly verify the model as it is not possible to perform a controlled experiment on an economy.

4.1 Time series data comparison (empirical validity)

The common method of validation for ECCO models is to run the model with about ten years historical data (Slesser, 1990., Crane and Slesser, 1995 and Slesser et al. 1994) By comparing the model data to the historical data the authors claim that this validates the model[7]. The most significant effects of growth over a ten year period are likely to be social rather than physical and so the model is unlikely to accurately map with historical data. In the "validity" test of the Australian economy Crane and Slesser (1995, p.65) had errors of up to 200%. However, most of the errors were much smaller and the general trends of the model are close to actual trends. It is questionable whether there is much value in using a ten year history of data for a model whose purpose is to analyse scenarios 60 years into the future. Ideally the data used to check the model should go back at least 50 years. Unfortunately there is no consistent data set to cover this time period in the New Zealand economy due to the Department of Statistics changing the collection of input-output data in 1977.

4.2 Energy balance

An energy balance is a useful check on the energy accounting in the model. It is easy to double count or lose track of energy, so the energy balance ensures that the accounting is consistent. The energy input to the economy must equal the embodied energy of the outputs minus the rate of change of embodied energy in capital stock. In the New Zealand model the only energy inputs are the primary energy supply and the embodied energy in the imported goods.

FENIN.K=PRIMES.K+IMPGD.K Total fossil energy input to the economy

FENIN	Energy into the economy GJ
PRIMES	Primary energy supply GJ
IMPGD	Imported goods GJ

The total embodied energy of the outputs is the sum of the outputs to final demand in each sector plus the embodied energy in the exports.

FENOUT=FIN2PER+FSR2PER+FDOMOUT+FTR2PER+FLS2PER+FTOTEXP

FENOUT	Embodied energy output or energy to final demand GJ
FIN2PER	Industry to final demand GJ
FSR2PER	Services to final demand GJ
FDOMOUT	Domestic demand GJ
FTR2PER	Transport demand GJ
FLS2PER	Life support to final demand GJ
FTOTEXP	Total exports GJ

The change in embodied energy of the capital stocks can be measured as the difference between the rate of capital formation and the rate of capital depletion.

FCHCPST.K=FTRCF.K-FTRDC.K

FCHCPST	Change of embodied energy in capital stock GJ
FTRCF	Total rate of capital formation GJ
FTRDC	Total rate of capital depletion GJ

FNENIN.K=FENIN.K-FCHCPST.K Net energy input

If the energy balances are correct then the FENOUT will equal FNENIN. Checking this energy balance is an excellent way of checking for errors in the program. Building up from a simple model with simple flows the energy balance is easy and intuitive. After each step, building the complexity of the model, the energy balance is checked. If a mistake has been made, it will show up in the energy balances. This has proved to be a very effective method of finding errors and understanding the model.

4.3 Input-output analysis as a check on the dynamic model data and structure.

Energy intensities from static input-output data are a useful check on the structure of the dynamic model. Because methods of calculating the embodied energy of the output are different, there can be a high degree of confidence if the solutions are the same in both cases. In earlier ECCO models the initial energy intensity of industry was first guessed, then adjusted until the energy intensity converged to a solution (Slesser, 1992a, Crane, 1995b). In the extended methodology, initial energy intensities are calculated from the static matrix analysis. This is an excellent check on the consistency of the

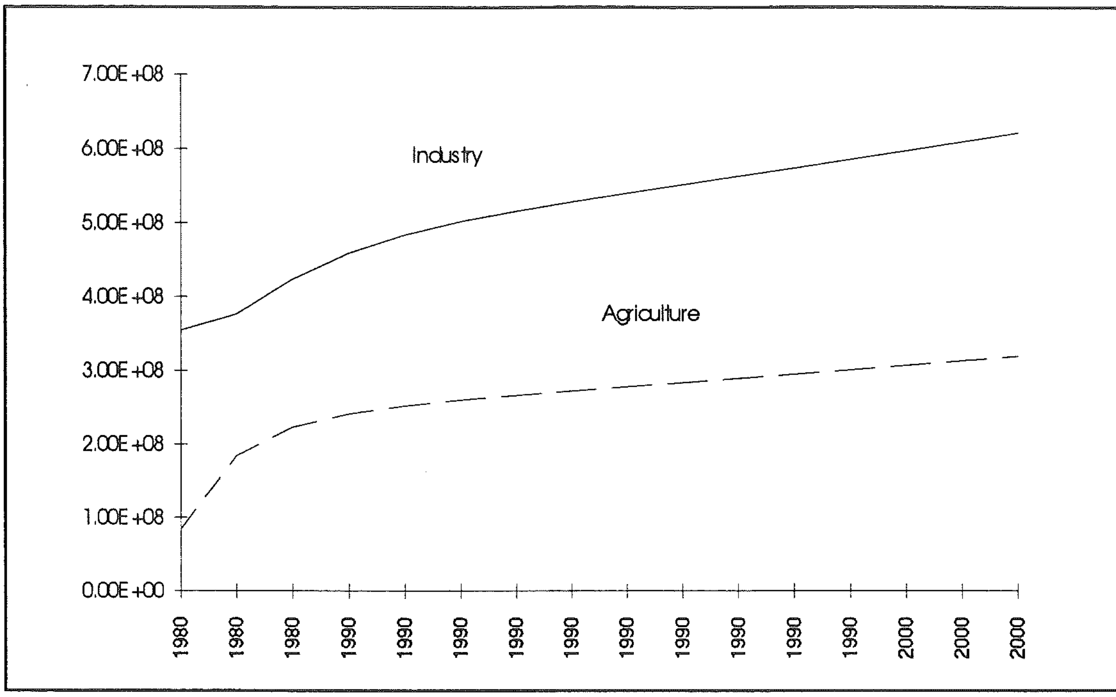

Figure 15-3 *Simulation with incorrect initial conditions*

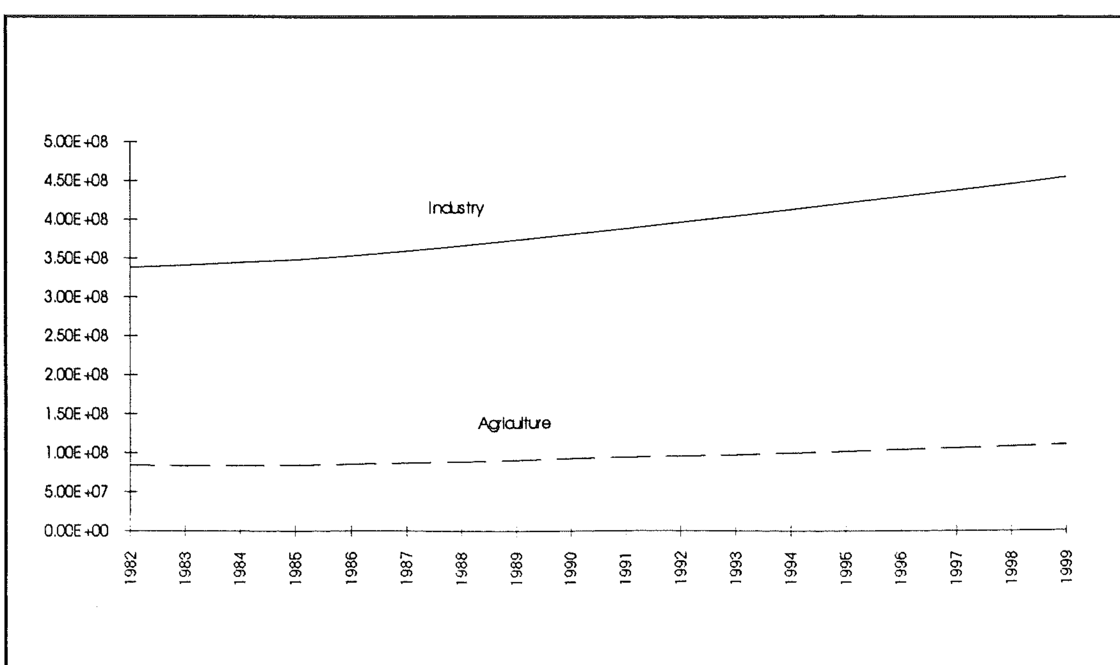

Figure 15-4 *Simulation with correct initial conditions*

model. Errors in data can also be detected because errors will result in inconsistencies in the initial dynamic simulation outputs.

If the outputs from each sector do not jump or drop significantly then the SEESM model will have calculated the outputs to be similar using a different method. The graphs in Figures 15-3 and 15-4 illustrate how errors were found in NZSEESM. When the model was initially simulated industrial output and agricultural output rose sharply indicating that the initial conditions did not match the model structure. Investigation showed that the thermal energy demand in the agriculture sector was incorrectly entered as 1.148e7 GJ instead of 1.148e6 GJ. The graph in Figure 15-4 shows the simulated results when the data is corrected.

This method is useful for detecting large errors but small errors may still be present as the energy analysis methods are different. Static energy analysis does not consider the energy embodied in the capital so one would expect small differences. The internal method of checking model consistency developed by Slesser and Crane will not detect errors such as the one described above but it will internally balance the initial conditions to be consistent with the incorrect data.

Notes

1. The model algorithms described in Appendix 5 have made the modelling procedure much simpler and easier to follow, so it would now be much easier to expand the model to include a higher level of input-output aggregation.

2. After developing this approach, it has been found that Noorman (1995), working at IVEM in Groningen, the Netherlands, is using a similar approach for an ECCO model of that economy.

3. The actual calculation of embodied energy in industrial ouput includes more terms.

4. The reason for this is that pollution control capital is usually added to existing capital and this can easily be done in NZSEESM.

5. An efficiency value of 1 assumes that the same quantity of electricity or thermal fuel is required to produce a unit of output as in the year of initiation.

6. See Chapter 13 for a full explanation of the double set of accounts and the set of additional capital accounts.

7. Slesser suggests that his model of the UK more accurately predicted economic activity and capital stock levels than the money based models of the U.K. Treasury or National Institute for Social and Economic Research (Slesser, 1990, p.22). Other formal statistical methods of comparing historical and model data have been developed by Sterman (1984).

Chapter 16: Simulation results from the New Zealand model

This chapter shows how the dynamic input-output model, described in the previous chapters, can be used to investigate possible physical consequences of scenarios in New Zealand. In each of the following simulations, one aspect of economic development is investigated. It is important that only one change is made at a time when comparing simulations. Some simulations investigated in this chapter include changing efficiency, changing structure of the economy, introduction of renewable energy technology and pollution feedbacks. The results of these models are compared to the results from other models to show how the modelling methodology is different. The implications for policy analysis are also discussed.

1 Scenarios versus predictions

The New Zealand economy is heavily dependent on the global economy, as are most small developed economies, and there are many international factors that may have a large effect in New Zealand. For example, there may be a significant nuclear accident in Europe or elsewhere that greatly increases the demand for New Zealand's agricultural exports. International trade and pollution conventions will also influence the quantity and type of imports and exports. Significant international influences are bound to happen over the time horizon of this model yet they *cannot* be predicted. This does not mean that the model is not useful. The aim of the model is to understand the critical physical flows and influences rather than to predict what will happen. The effects of a major international influence can be simulated to see how the New Zealand economy might react. This type of simulation may help understand how to prepare for such an event.

2 Scenarios for the New Zealand economy

Several different scenarios for the New Zealand economy have been tested as they show the types of development options that can be investigated. The following scenarios are discussed below:

- Business as usual
- Change in general growth rate
- Change in sectoral growth rates
- Effect of energy efficiency
- Renewable energy technology
- Pollution control

In each simulation the general trends of the model generally confirm what we intuitively suspect. For example, increases in efficiency reduce energy demand, a growing economy increases energy demand etc. The New Zealand model gives a quantitative measure of the changes in energy demand for specific scenarios to allow the policy analyst to gauge the relative significance of different options.

2.1 Business as usual

The "business as usual" or "continuation" scenario is used as a base case to test the effect of changing different parameters in the model. This case is not necessarily any more likely to happen than another scenario and can easily be changed if one wishes to use a different base scenario.

Much of the baseline data is based on the assumptions in the Ministry of Commerce (MoC, 1992) baseline forecast and the electricity supply and demand discussion paper prepared by the Electricity Corporation of New Zealand (ECNZ, 1994). The main "drivers" of the model are briefly discussed below, but more detail on the data sets used for the models is given in Appendix 4.

In many economic models scenarios are built on assumptions about economy-wide GDP growth rather than how specific sectors grow. One advantage of the dynamic input-output model is that the growth rates of different sectors can be specified rather than a general growth rate. The ECNZ model makes the distinction between growth in household consumption (1.6%) and growth in exports (2.7%). This gives an overall growth rate of about 1.8%. A similar assumption about growth rate is used in the MoC report[1].

The business as usual energy efficiency improvement estimations are based on the MoC energy efficiency scenarios[2]. Variant 1 is a continuation of present trends and Variant 2 is an accelerated energy efficiency program. Both scenarios recognise that energy efficiency rates will not be the same in all sectors. The figures are annual rates of improvement in energy efficiency. The results of the Variant 2 scenario are discussed in section 2.4.

Energy demand sector	Variant 1	Variant 2
Residential	-0.5%	-1.0%
Industrial commercial	-1.0%	-1.5%
Transport	-0.5%	-1.0%

It is debatable whether the efficiency improvements can continue at the same rate for the next 60 years. The aim is not to resolve this point but to have some semi-realistic base scenario with which to compare different scenarios. It is assumed that no additional capital is required to improve the efficiency (this simplifying assumption is removed in section 2.4).

Other assumptions in the business as usual scenario:

- Population growth continues at the current rate of 0.8% pa
- Imports to each sector increase relative to the growth of the sector.
- Relative prices of imports and exports remain the same[3].
- New thermal energy demand is met by importing fuels.
- New electricity demand is supplied by a combination of hydro and thermal sources[4].

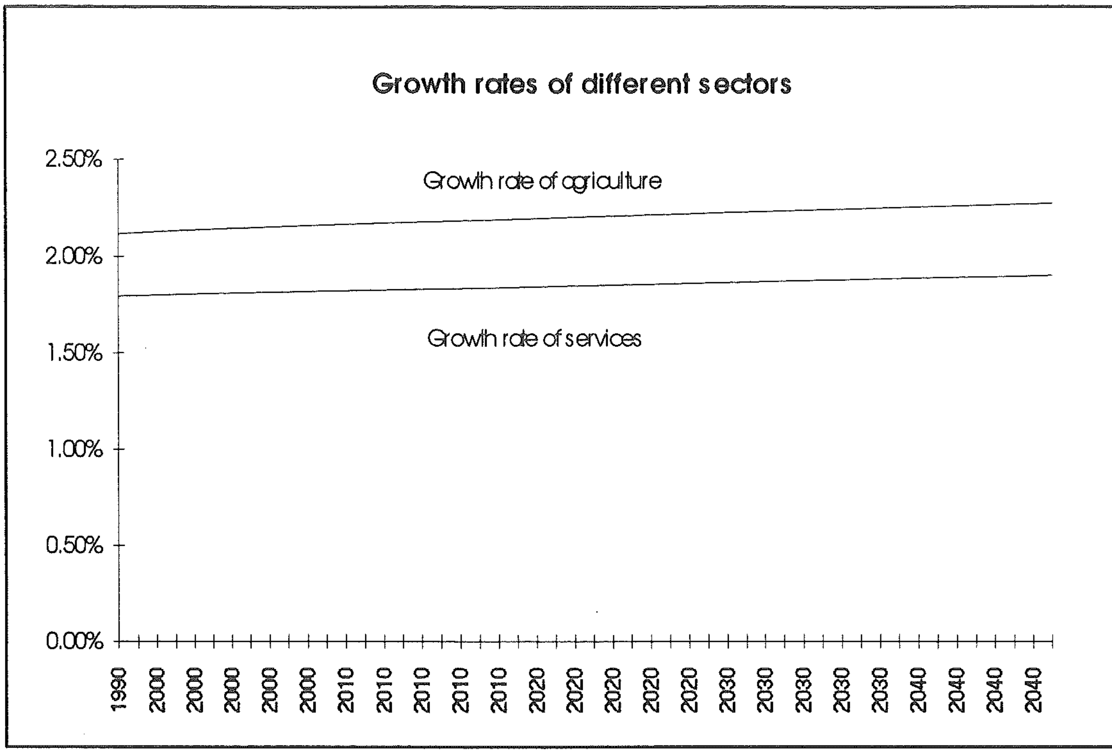

Figure 16-1 *Growth rate of services and agriculture in a base scenario*

Because the growth rates to final demand and the growth rate to exports are different, the growth rates of each sector is different. For example, sectors with a high proportion of exports grow at a higher rate than sectors with a low proportion of exports - Industry and Agriculture grow at about 2.1%. The average overall growth rate of economic

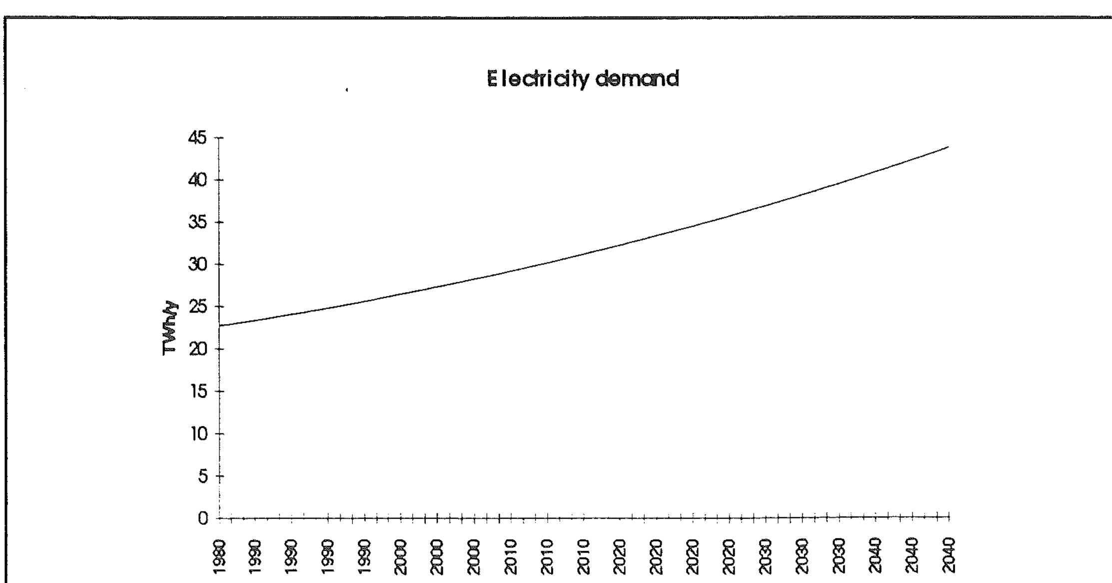

Figure 16-2 *Electricity demand in a base case scenario in New Zealand*

output is about 1.9%. In this scenario growth rates are slowly increasing because the fraction of each sector that is exported is increasing so the overall growth rate of each sector will be increasing. Some of these growth rates are shown in Figure 16-1.

Results of simulations show that electricity demand continues to rise noticeably in this scenario even with the increases in efficiency. Electricity demand is less than that for the ECNZ model, as there has been no assumed inter-fuel substitution[5]. Thermal fuel demand also increases at about the same rate.

2.2 Change in growth rate of the economy.

The simplest change that can be made to the model is to change the general growth rate. As expected, this will greatly change the energy demands and therefore carbon dioxide production. Figure 16-3 shows the effect of different average growth rates of the economy over a 50 year period, on carbon dioxide emissions. These scenarios assume that the technology mix is the same and that efficiency improvements of the

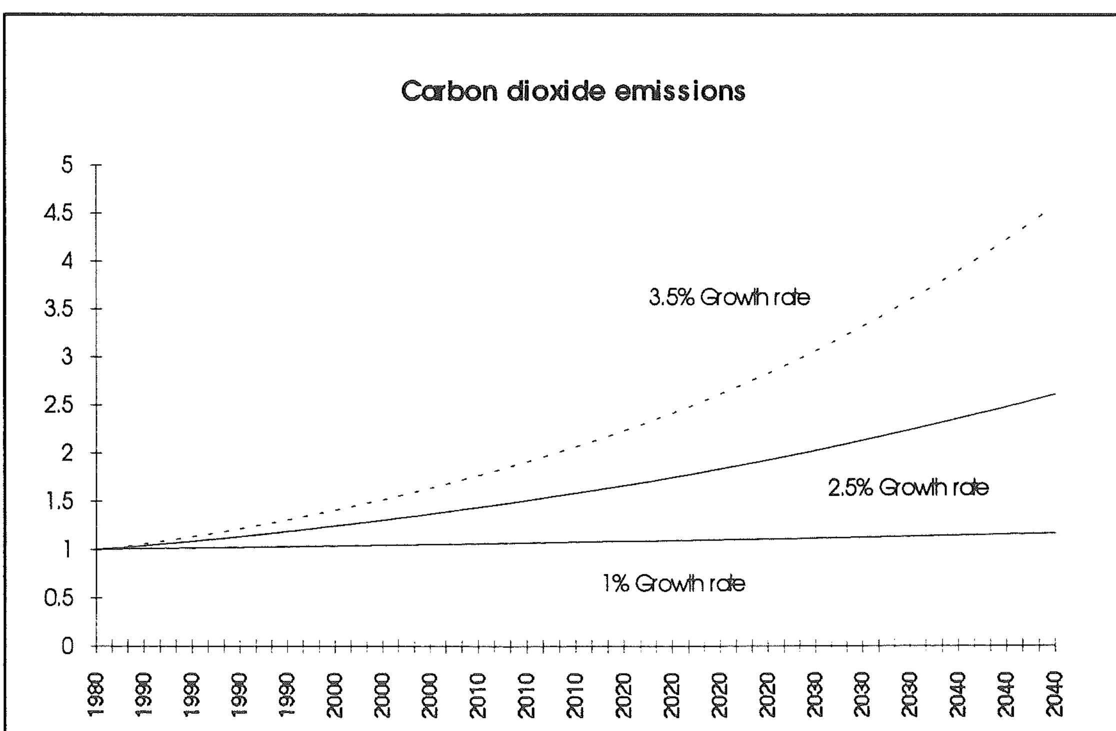

Figure 16-3 Carbon dioxide emissions with different economic growth rates

past continue in the future. The three different scenarios assume general growth rates of 1, 2.5 and 3.5 percent per annum. For the low growth scenario the carbon dioxide emissions barely rise, as they are off set by increases in efficiency. The high growth rate scenario increases carbon dioxide emissions by a factor of 4.5 over 60 years.

2.3 Change in the relative growth rates in the economy

The flexibility of the dynamic input-output model allows for the relative rates of growth of different sectors to be simulated. This scenario illustrates how changing the growth rate of one sector affects the overall growth of the economy and associated physical flows. As an example assume that the average growth rate to final demand and exports is 1% per annum in all sectors, except for services to final demand which is set to grow at 3% per annum[6]. The difference between growth rates in this scenario is large, to illustrate the significant effects indirect energy demands can have. For simplicity assume there are no improvements in energy efficiency. A comparison of the direct and indirect energy demands is shown below.

Direct energy analysis

Total electricity demand[7]	= 22.730e9 kWh
Electricity demand from services sector	= 3.277e9 kWh
Fraction services to final demand	= 0.546
Electricity services to final demand	= 3.277e9 * 0.546 = 1.789e9 kWh
Other electricity demand	= 22.730e9 - 1.789e9 = 20.941e9 kWh

Electricity demand after 60 years	
Electricity services to final demand	= 1.789e9 * (1.03^{60}) = 10.540 kWh
Other electricity demand	= 20.941e9 * (1.01^{60}) = 38.043e9 kWh
Total electricity demand	= 10.540e9 + 38.043e9 = 48.310e9 kWh

When this scenario is simulated the total electricity demand is 57.3e9 kWh which is significantly higher than the figure of 48.3e9 kWh found from a direct energy analysis.

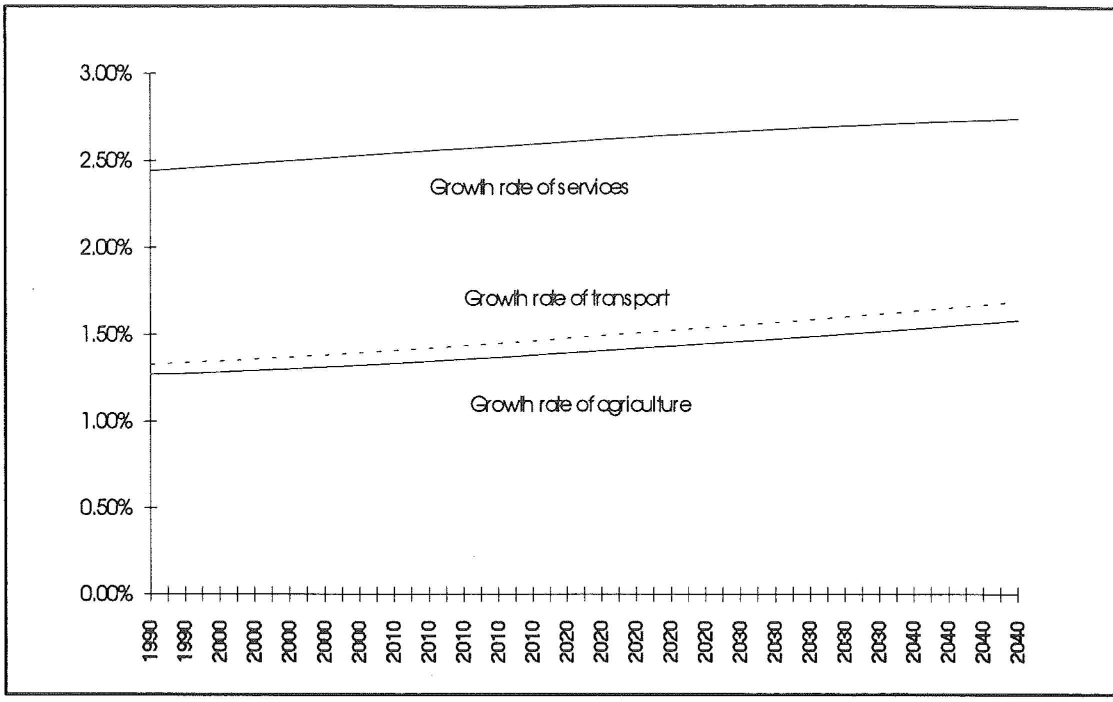

***Figure 16-4** Different sector growth rates for a scenario with a high growth rate in services.*

The reason why the electricity demand is higher is that as the services sector grows it requires inputs from other sectors of the economy and these sectors in turn have their own electricity demand. To illustrate this the, growth rates of some sectors are shown in Figure 16-4. As one would expect, the overall growth rate of the services sector is much higher than the other sectors. The sectors with more inputs to the services sector, such as transport, grow at higher rates than those sectors with lower inputs to services, such as agriculture. All the growth rates increase over time because the fraction of output to services increases so the overall growth rate of the sector will increase over time.

An interesting scenario option is that of increased growth of a low energy intensity sector. It has been widely argued that this type of economic development will reduce dependence on physical resources. The scenario below shows that when a sector with a relatively low direct energy demand grows it is likely to have a bigger effect on energy demand than expected, because of the indirect energy requirements.

2.4 Changing efficiency

The quantity of energy used for economic activities can reduce, due to technologies that improve the energy efficiency of the sector. Past trends in energy efficiency and an accelerated energy efficiency scenario were given in section 2.4 above. Figure 16-5 shows the energy demand for each of these scenarios, along with a scenario where there is no improvement in energy efficiency. As one would expect, energy efficiency has a significant influence on energy demand.

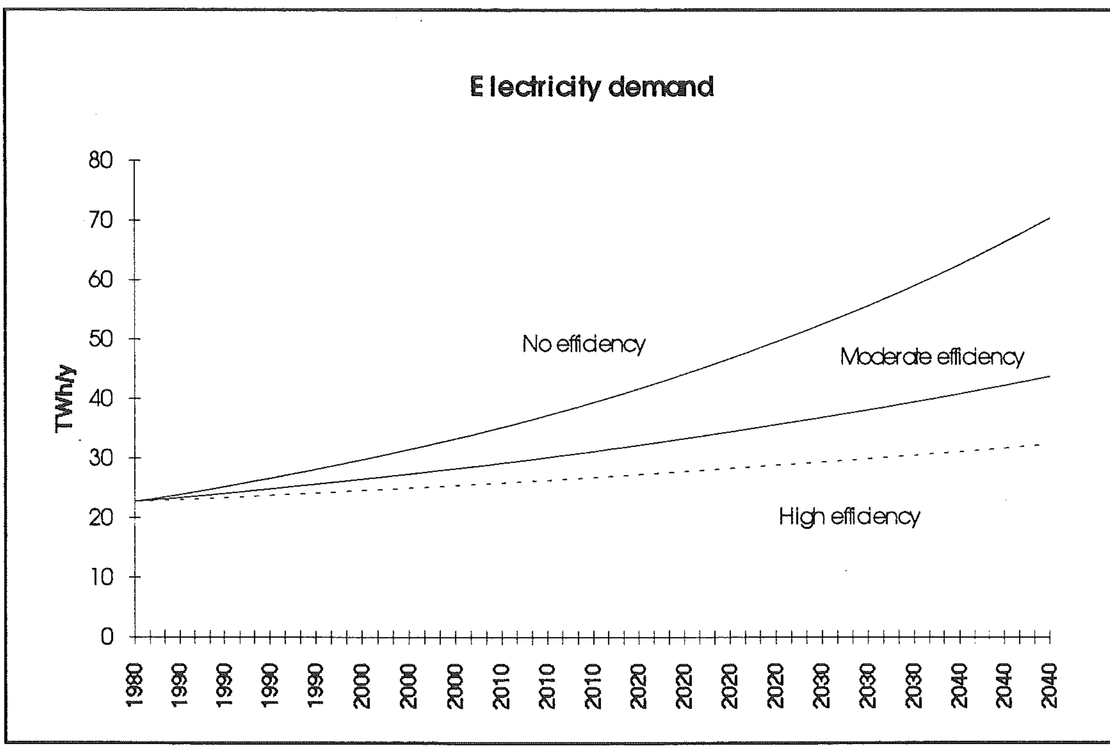

Figure 16-5 The effect of efficiency improvements on electricity demand

In the previous scenario it is assumed that energy efficiency requires no extra capital. The energy efficiency increases as new capital replaces old capital. Figure 16-6 shows what would happen if the investment required to improve the efficiency added an extra 10% to the cost of the capital. The graph shows that production of physical capital by industry significantly increases electricity demand. Here, it is assumed that capital is supplied from within the economy rather than imported. If one assumed the capital was imported, then there would be no change in the energy requirements of the economy and only the balance of payments would change. Alternatively, it may be assumed that

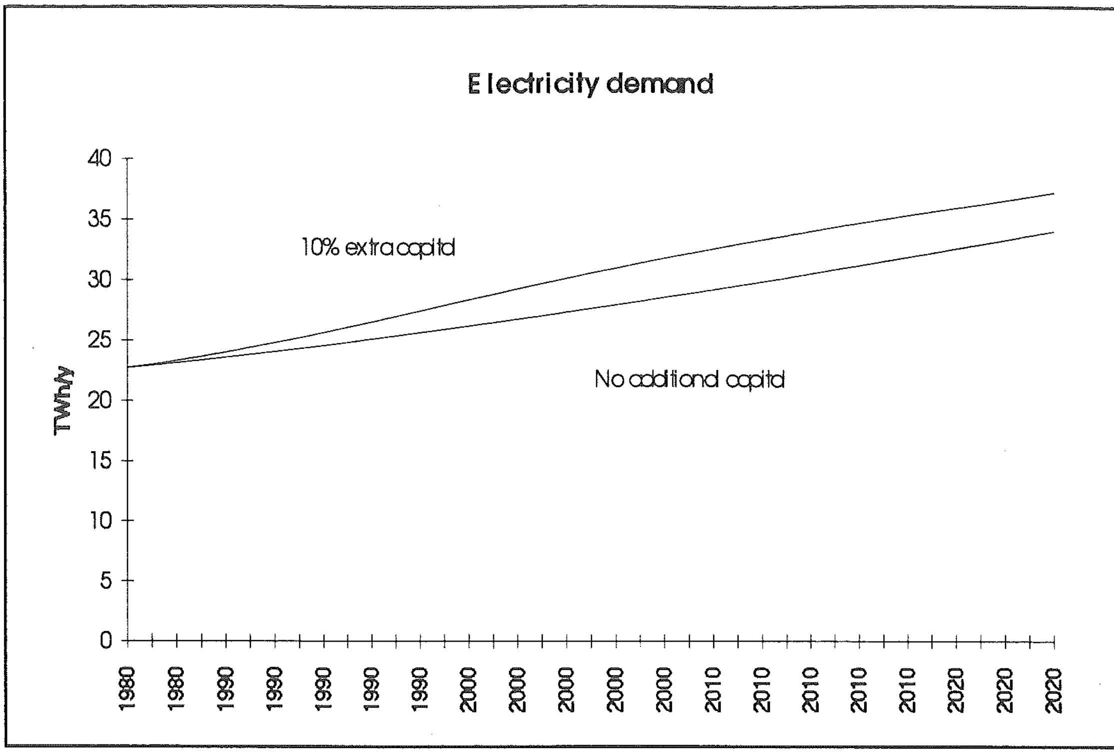

Figure 16-6 *The effect of additional capital on electricity demand*

capital is imported and that exports are increased to balance the extra cost. It is very easy to change simulation options to see how they effect the internal energy requirements. The model's flexibility allows a number of simultaneous changes such as specific growth rates, capital requirements and efficiencies to be modelled.

2.5 Renewable energy technologies

A policy aim for an economy may be to reduce carbon dioxide emissions. In this scenario the option of increasing the fraction of energy supplied by renewable energy technologies is investigated.

In this scenario the fraction of thermal energy from renewable sources is increased to 70% by the year 2042. One could assume the new sources of renewable thermal fuel include wood, methanol and other biofuels. A more detailed scenario would specify particular technologies in detail and all the inputs required. This is just a general scenario, to show the types of development options that can be investigated. As one would expect, this scenario significantly decreases net[8] emissions of carbon dioxide

(Figure 16-7).

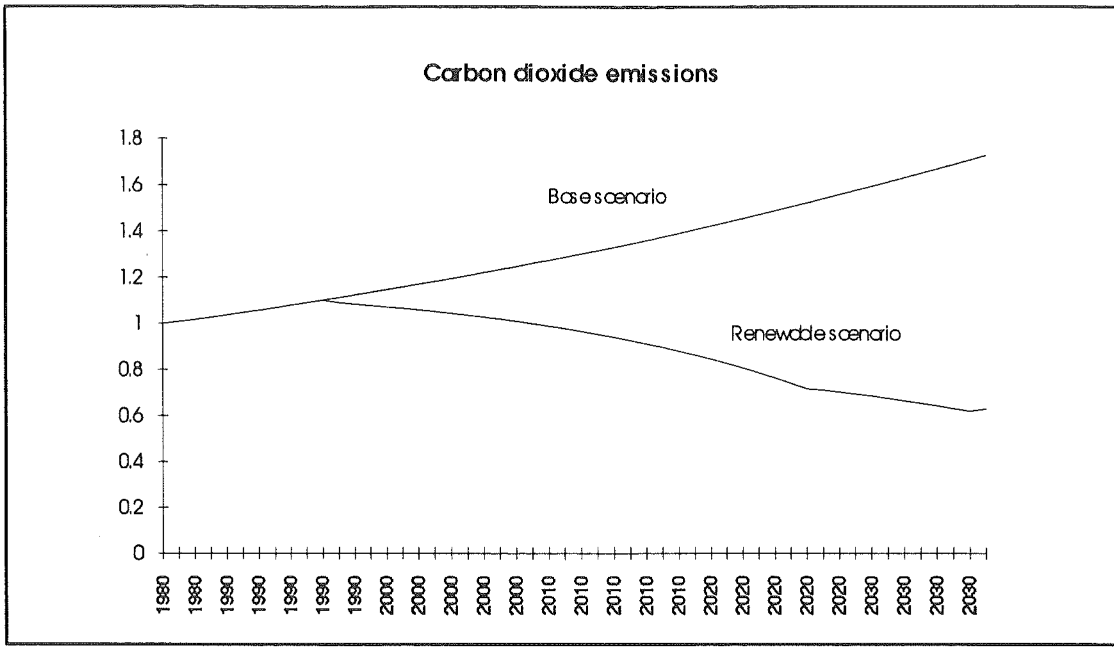

Figure 16-7 Carbon dioxide emissions with the introduction of renewable technologies

Figure 16-8 shows thermal energy demands for the renewable energy scenario and the base scenario. In the base scenario all of the new thermal energy demand is supplied by importing fuels. In the renewable scenario it has to be produced within New Zealand and this requires inputs of capital and energy. That is why the energy demands are

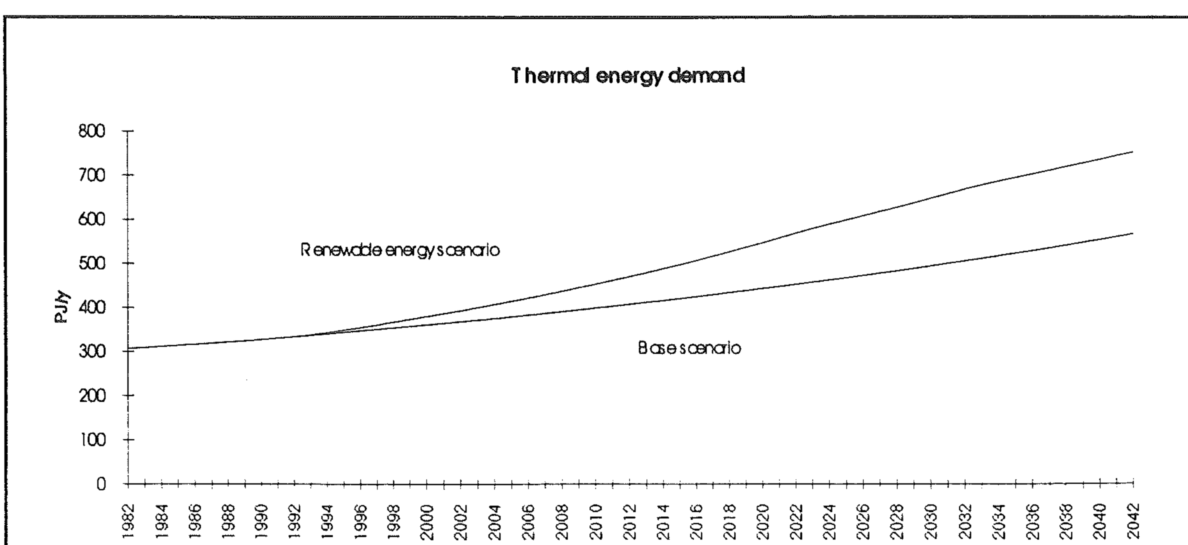

Figure 16-8 Thermal energy demands for a renewable energy scenario

significantly higher for the renewable energy scenario[9]. This is important information for the those involved with energy planning. The scenario does not reduce carbon dioxide by as much as one would expect because of these increased indirect energy demands.

2.6 Pollution restrictions

Many pollution feedbacks can also be included in the model. For example, highly intensive farming is thought to, in some cases, reduce the long term potential of the land to produce agricultural products. Thus, future agricultural production may be a function of the type of agricultural production used previously. In another scenario renewable fuel technologies may require farm land, and this may reduce farm production. This in turn may increase the energy and capital demands in the agriculture sector if one wishes to maintain conventional agricultural production at current levels.

Pollution control methods can also be simulated. As an example, carbon dioxide may be captured[10] or the atmospheric weather may be controlled[11]. In each case there would be certain capital and energy inputs that will affect resource demands and pollution output. The new capital may cause more carbon dioxide production that the policy was designed to prevent. NZSEESM enables one to investigate such a scenario.

There are many other ways in which pollution can be simulated and it is just a matter of finding the appropriate information and introducing a feedback. For example, solid waste will be a function of the rates of capital depletion and consumption. Of the solid waste a fraction may be polluting, inert or biodegradable (see Chapter 7). The model would need to be much less aggregated to achieve useful information on many specific pollutants. Effects of these specific feedbacks could also be included if they are known.

2.7 Additional policies that could be tested

The following is a list of possible physical policies that could be tested using the model. The model provides a check that the policy will achieve the desired goal.

- What would be the best way to maintain New Zealand's energy self-sufficiency above 70%?
- Which is better from an energy point of view, wind turbine generated electricity or electricity from biomass fuel?
- What would happen if there was a large increase (or decrease) in the quantity or type of trade?
- What would happen if fossil fuel imports were limited in the short to medium term? What would be the best strategy to cope with this possibility?
- What are the pros and cons of using increased efficiency or renewable energy technologies as methods of reducing carbon dioxide emissions?

3 Indicators of sustainable development in NZSEESM

The previous sections illustrate some possible scenarios for development in New Zealand. From those simulations there are several indicators that give insight into the question of sustainable development. The indicators include the relative size of the physical economic services sectors, the embodied energy information and technology assumptions.

3.1 Indicator of the size of environmental services

The sectors of the economy that are most important for the analysis of sustainable development are those that have a direct interaction with the environment. These sectors are defined and explained in Chapter 7 and are named "environmental services." In NZSEESM these are the electricity, thermal fuels and agriculture sectors[12].

It is difficult to estimate the size of the environmental services of an open economy. The reason for this is that some physical economic services may be imported and this may change over time. For example, the quantity of fuels imported and agricultural goods exported will change the fraction of the economy that is invested in the environmental services. In some simulations the fraction invested in environmental services will increase. For example, in the renewable energy scenario above, the fraction of capital invested increases from 23% to 26.5%. This suggests that more effort is going into interacting with the environment. An associated indicator is the quantity of energy required by the environmental services.

3.2 Embodied energy indicators from the model

The discussion in Chapter 8 outlined why energy has an important role in the economy. The degree of importance maybe debatable but in our opinion it is well worth having an extra indicator to aid the policy analysts. Direct energy requirements are often not a good indicator of the true energy required to make a good or service available.

The direct fossil energy (DFE) requirements are a total of the thermal energy demand and the electricity demand multiplied by the thermal energy required to provide the electricity. The direct fossil energy for each sector of the economy can be calculated. For example:

DFESER.K = TEDSER.K + EEDSER.K*ELFE.K

DFESER	= Direct fossil energy services
TEDSER	= Thermal energy services
EEDSER	= Electricity demand services
ELFE	= Thermal energy required to produce electricity

From this the fraction of direct energy (FDE) used in each sector of the economy can be calculated. They are then compared to the fraction of total embodied (FTE) fossil energy required to each of these goods at final demand.

The pie graphs in Figures 16-9 and 16-10 show the fraction of direct energy and total embodied energy required in different sectors in the economy. This shows that the sectors of the economy that have low direct energy requirements such as services have quite high indirect energy requirements. That is, the input from sectors such as transport and industry increase the indirect energy demand from the services sector. The indirect energy in the domestic sector includes all the energy required to provide capital to the domestic sector. The transport sector is low as this is only commercial transport. Private transport is included in the domestic energy demand. The total energy required in the transport sector to final demand is quite low as most of it is included as indirect inputs to provide outputs for other sectors.

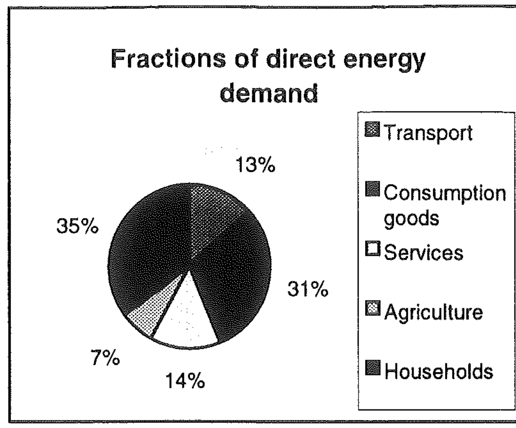

Figure 16-9 Fractions of direct energy demand is each sector of the economy

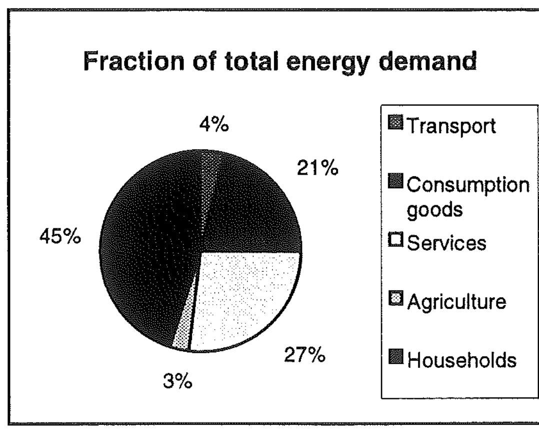

Figure 16-10 Fractions of total energy demand in each sector of the economy

The advantage of the dynamic energy analysis is that this type of analysis can be done for any different scenario to see what are the effects a policy may have on the indirect energy requirements. The graph in Figure 16-11 shows how the fraction of total energy changes when the services sector grows as in scenario 2.3 above.

The analysis of direct and indirect energy demands gives different insights into technological options. A particular technology may reduce the direct thermal fuel demand but not the overall energy demands. Two different technologies for water heating can be compared in an example of a system to supply 100 GJ of heat to water.

Gas technology @ 80% efficiency	Total use 125 gas GJ/year
Heat pump technology @ 250% efficiency	Total use 40 GJ/ year

This simple comparison would indicate that the heat pump technology is much more efficient. If, however, the electricity is supplied by a thermal power station that is 35%

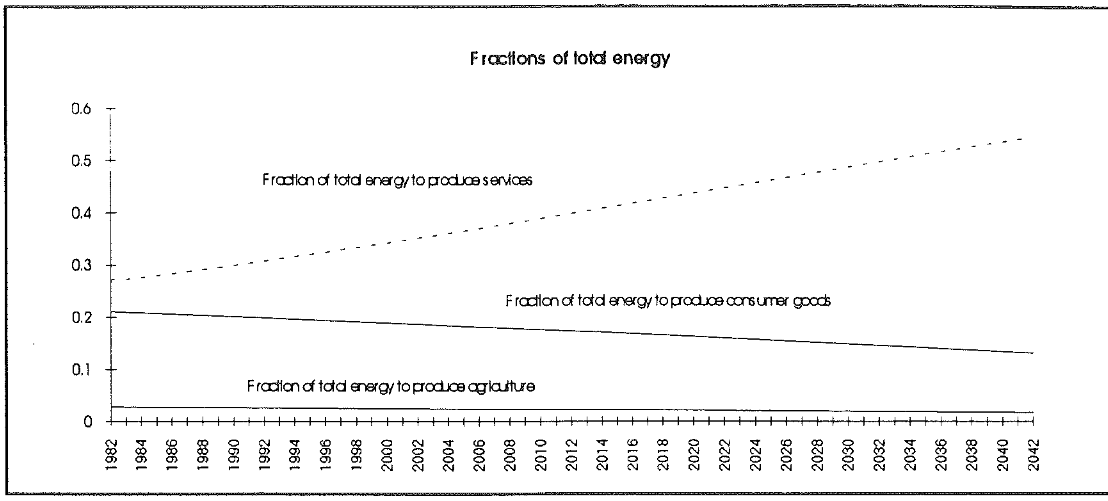

***Figure 16-11** Fraction of total embodied energy used in some sectors of the economy if services grow as in the scenario in section 2.3.*

efficient the total energy use for the heat pump technology is 114 GJ. If extra embodied energy required to produce the heat pump is also included the heat pump technology may actually increase the overall energy demand of the economy.

As discussed in Chapter 8 one of the difficulties with energy analysis is the problem of adding energies of different qualities. The conclusion from this discussion was that different types of energy analysis give different indicators and neither is necessarily right or wrong. In NZSEESM it is possible to change between calculating the embodied fossil energy or the embodied commercial energy (it is possible to calculate both simultaneously). One will give a measure that is of interest to carbon dioxide planners and the other gives an indication of the relative physical difficulty of tasks in the economy. The next logical step in the development of this model would be to look more closely at the pros and cons of different types of energy analysis[13]

3.3 Technology limits and indicators

So how does this model help understand physical limits? The difference between a high growth and a low growth scenario is in the assumptions made about the rate of technological progress in each sector of the economy. Although it has long been recognised by economists that these technological coefficients are the key determinants of economic growth, their models offer few insights into how these factors may change in the future. Most economic growth models assume a linear extrapolation of current technology trends. The aim of the SEESM model is to try to understand the technology trends by splitting them up into different sectors and understanding how physical laws affect likely changes in technology. Chapter 10 outlined how energy analysis may give insights into ways the long term technological coefficients may be limited. The model is set up so any trends in learning can be included in the specific sectors of the economy. This is one promising area for further investigation.

In NZSEESM the growth rates and rate of increase in labour productivity are stated in all but the industry sector. Labour productivity is calculated in this sector as the output divided by the remaining labour available. If this is too high then the assumptions about labour productivity in other sectors must be increased or the labour supply increased. The aim of this algorithm is not to predict the relative rates of change in labour productivity but to explicitly analyse the technology assumptions for different scenarios.

An example of the type of scenario that can be analysed is a change in the participation rate of the population. In many industrial economies workforce participation is predicted to drop due to the "baby-boomers" reaching retirement age[14]. This has significant effects on the technological assumptions of the model. If one wishes to maintain a certain growth rate in output per person and the number of people working to produce it is diminishing then the output produced per person must be growing at a higher rate. This implies a higher rate of technological change.

4 Comparison of NZSEESM with other models

The purpose and results of NZSEESM are compared to other models to understand how they relate to each other. The comparison between NZSEESM and a version of the UK ECCO model outlines the improvements made to the New Zealand model. NZSEESM is also compared to conventional econometric models and the Club of Rome models.

4.1 Comparison with the ECCO models.

NZSEESM is quite different from the ECCO models developed by Slesser and colleagues and the main theoretical differences are discussed in detail in Chapter 13. Some other improvements in the model relate to the structure and data base of the model. Several checks on the data and structure of the model have also been developed (see previous Chapter).

Because the model is based on input-output and capital stock data already collected in most economies it is relatively easy to collect accurate consistent data compared to the ECCO data structure in Slesser's models. The structure of the model is such that each sector is very similar in terms of the types of inputs, outputs and exogenous factors. The same calculations are performed on each sector, so to understand the whole model one only needs to understand the calculations in one sector. The result of this is that it sould be possible to expand the input-output structure used here to include more sectors.

UKECCO (Slesser et al. 1994) has much more data on a whole range of things such as taxation, social security, health, education etc. yet it has a much simpler input-output structure. A Table in Appendix 2 shows that many input-output relations are assumed to be zero. Most of the emphasis appears to have been put into building more detailed models but in an apparently ad hoc way. The result is a model that is somewhat unstructured and difficult to follow.

4.2 Comparison with the "Limits to Growth" models

In both the "Limits to Growth" (Meadows et al. 1972) and the ECCO models of Slesser, physical assumptions are first made about the links within the economy, then the model is simulated. The difficulty with this is that it appears to be predicting what will happen in the future[15]. A less controversial method of modelling is to propose a growth scenario then let the model calculate the physical assumptions required to make that scenario happen. This allows the physical assumptions to become the focus of the model. It makes it seem more like a simulation exercise rather than a prediction exercise.

Because the model is based on a national economy rather than a global economy we believe it is more useful to the policy analyst. The input-output structure also allows a far greater range of policies to be investigated and direct links to conventional economic model can be established.

4.3 Comparison with energy demand models

The models described above are quite different from conventional econometric models such as those used to produce the energy forecasts in New Zealand (MoC, 1991). These models predict energy demands by estimating an overall GDP growth rate, changes in relative prices and elasticities. The focus of these models is on how human demand will respond to changing prices.

NZSEESM was not designed with the specific purpose of simulating future energy demand, but because of the focus on energy flows the model is a powerful tool for understanding future energy demand. The simulations in sections 2.1 to 2.7 above show how a wide range of scenarios can easily be investigated to give useful information to the energy policy analyst. The dynamic energy analysis within the model gives added information to the energy planner. At the moment NZSEESM is set up to calculate the total embodied fossil energy required for each activity in the economy. Carbon dioxide emissions will obviously be directly related to embodied fossil energy, so this will help analyse carbon dioxide control methods. The energy analysis may be switched to include only embodied electricity. In this way the total quantity of electricity required to produce goods at final demand could be estimated. This would be of interest to companies involved in the producing and distribution of electricity.

The advantage of a dynamic model with capital stocks is that it allows the dynamics of transition to be calculated. For example, the energy efficiency of capital stock cannot change instantly; the same goes for labour productivity etc. Any transition will take time, and accelerating it will have significant other effects on the economy that can be quantified in this model.

4.4 Comparison with conventional economic models

Because the purpose of conventional economic models and NZSEESM is different the structures of the models are significantly different. Instead of focusing on prices and elasticities NZSEESM emphasises the factors that are significant for physical restrictions such as feedbacks, structure and energy flows. In short term human behaviour economic models the input-output structure is usually assumed to be constant and this is usually a valid assumption for the time frame of the model. However, these structural changes and feedbacks are significant for the long term physical model. An advantage of the simulation model is that it is very easy to change assumptions and do another simulation. This flexibility allows a wide range of simulations to be investigated easily.

Conventional economic models are generally designed to examine short term influences on economic growth. Some important short term factors include things such as business confidence, exchange rates and interest rates. It may be that some policies will affect short term economic growth due to a fall in "business confidence". This may be illustrated by the possibility of a government that places more emphasis on environmental issues. The physical characteristics of the economy would be the same but the short term growth rate might fall due to a decrease in "business confidence". The short term growth rate is likely to be influenced more by how the business community perceives a policy than by the direct physical consequences of that policy. The point of discussing this is to stress that short term influences on economic growth caused by unknowable political changes cannot be predicted by the model. However, one could include such a political change as a scenario option.

The role of NZSEESM should be as a check on policy options to see if the policy could actually achieve the desired goal. For example, is a carbon dioxide target more easily met by encouraging energy efficiency or solar energy? The model shows the physical consequences of each of the different policies. It has been argued that reduction in energy and resource use will be naturally achieved as we switch to a services orientated economy. The simulation in section 2.3 shows that this is unlikely given the substantial indirect energy requirements of the services sector.

Because the model includes an analysis of embodied energy the model can be used to estimate by how much the price of goods in each sector would be affected by an energy tax. Therefore, if one wished to exempt exports from this tax and/or add it on to imports this would be an easy way to calculate it. Calculating tariffs to allow fair trading has been identified by Constanza (1994) as one of the key policies needed to achieve sustainability. Without it any initiative by a country to achieve sustainability may effect its international competitiveness.

5 Discussion on possible limits on the New Zealand economy

It is widely recognised that environmental and resource concerns are likely to affect economic performance. For example, Tinbergen and Hueting state that:

> Saving the environment will certainly check production growth and probably lead to lower levels of national income. This outcome can hardly surprise. Many have known for a long time that population growth and rising production and consumption cannot be sustained forever in a finite world (Tinbergen and Hueting, 1991, p. 38).

NZSEESM can be used to clarify the physical flow requirements for different long term scenarios. The main focus of this thesis has been to develop a tool to investigate long term physical limits, rather than apply it in detail to the New Zealand economy. More work would be required in the data analysis to draw firm policy conclusions. The following discussion gives some thought on New Zealand's limits and how the NZSEESM model can help analyse them.

It appears highly unlikely that there would be a food shortage in New Zealand due to the large quantity of land per capita. Predicted pressures on food production internationally (Brown, 1993) may in fact be beneficial to the New Zealand economy. Perhaps the biggest concern for New Zealand involves global issues such as carbon dioxide production. If the theorised changes in climate were to happen this would have a huge effect on the New Zealand economy due to a relatively high proportion of agriculture and forestry. New Zealand is in a very fortunate position in that it has several options for reducing carbon dioxide production. In New Zealand it seems the most likely method of controlling carbon dioxide emissions is by offsetting them with forest planting. The result of this is that a switch to alternative fuels may not be likely for sometime. Not many countries are in such a fortunate position as to have their carbon dioxide problems solved by an already profitable business. New Zealand also has many possibilities for solar energy production such as wind, hydro electricity and biofuels.

Not enough time has been put into the analysis of specific technological limits in the New Zealand economy but there appear to be no immediate limitations. Some general trends such as an increasing investment in research and development for a smaller economic growth rate suggest that some technological limits may be being approached.

5.1 The role of government

The benefits of sustainable development are usually not captured by the party who pays for it. It will benefit the whole society and in particular generations to come (social, economic environmental and cultural benefits). A market economy will not ensure optimum investment in sustainable technologies, therefore there is a need for some form of government intervention. It is the role of governments to look at these long term possibilities, as the average person and business usually does not have the time or resources to analyse them. Once possible problems have been identified, the role of the government is to design and implement policies to minimise risk at an acceptable cost to the population. In essence any analysis or environmental policy is an insurance policy against possible negative influences on the economy.

The concept of government policy as an insurance policy is best discussed with specific reference to a policy such as carbon dioxide emissions. Part of the insurance will be to prepare methods to use market forces to help get reduction in carbon dioxide to an acceptable level. Examples of this include analysis of the relative merits of permits, regulation or taxes to achieve carbon dioxide goals. The other part of the insurance may be seeding pilot projects and research[16]. For example, if we wish to continue present levels of economic growth and reduce carbon dioxide then how can this best be achieved? What is the best insurance policy - research in renewables or energy efficiency? This type of question cannot be answered without reference to a long term physical flow model of the economy such as NZSEESM.

Notes

1. The assumptions in each of these reports had a growth rate that fluctuated according to how they thought growth rates would change from year to year. This sort of scenario can easily be put into NZSEESM but for simplicity the average growth rate for the period is used.

2. No distinction is made between the thermal energy efficiency and the electricity fuel efficiency (this distinction is made in the ECNZ report) although it can easily be included.

3. For example the price New Zealand gets for agricultural exports is constant along with the price paid for imported goods such as oil.

4. For simplicity sake it is assumed to be supplied in the same ratio as currently supplied. That is, the same ratio of hydro and thermal electricity generation.

5. In the ECNZ model it is assumed that electricity will replace other fuels in some parts of the economy.

6. This is done in the model by setting GRPER (growth rate to final demand) = 0.01, GREXP (growth rate of exports) = 0.01 and GRSR2PR (growth rate of services to final demand) = 0.03. This model is called NZSTRCT.DYN.

7. This type of analysis is easily done for all energy rather than just electricity as in this example.

8. It is assumed that renewable thermal fuels do not increase net carbon dioxide due to the fact that carbon dioxide is absorbed when the biomass is grown.

9. Much more effort needs to be put into the analysis of future inputs to renewable fuel technologies so the internal energy requirements can be more accurately simulated.

10. Some proposed technologies for the removal of carbon dioxide include injecting it into old petroleum fields, using algae and freezing and storing.

11. Mantner (1993) proposed that satellites may reflect some sun away from the earth to prevent warming. This seems ironic given that many proposals have been put forward to divert more solar energy into earth as a means of energy production.

12. A more detailed model will include pollution control and materials sectors.

13. This topic is currently being researched at Massey University (Palmerston North, New Zealand) in the Energy group under the guidance of Dr Patterson and Prof Cleland. Of particular interest is developing the "Quality Equivalent Methodology" developed by Patterson (1993).

14. This is easily included in the population model by splitting the population into different age groups (Slesser et al. 1994).

15. It should be stressed that the results of Meadows et al. were never claimed to be predictions, only simulations. However, the results were interpreted by many as predictions. They could have simulated an "optimistic" world scenario and used the model to identify the physical assumptions required to make that happen. This way it is clear that the model is being used to understand and identify critical physical assumptions required for growth so they can be openly debated.

16. Funding for the Energy Efficiency Conservation Authority (EECA) and the Ministry for the Environment are examples of this.

Chapter 17: Conclusions and further work

The focus of this thesis has been on developing a useful methodology for analysing physical limits and a limited amount of time has been allocated to applying it to the New Zealand economy. Other studies have a greater level of detail in their models (Slesser et al. 1994) but because some of the underlying methodology is questionable (see Chapter 13) the conclusions that can be drawn from the models are also questionable. The methodology discussed in this thesis has been developed to the stage where it is a policy tool to complement conventional economic models.

1 Purpose of the analysis - need for a physical model

The concept of sustainable development is extraordinarily broad and vague. The problem analysed in this work was narrowed down to the identification of long term *physical* limits on economic growth. In particular, it was identified that there is a need for a physical analysis of economic growth, technological development and resource scarcity. Conventional economic approaches to sustainable development are useful for short to medium term but they are not designed for long term analysis where there can be significant structural change in the economy.

Many important issues relating to sustainable development involve ethical choices. The model developed here cannot resolve ethical dilemmas but it helps to separate ethical issues from physical issues. The other important role of the model is that any assumptions have to be explicitly stated in the model so they are open to scrutiny. The model helps to understand the critical factors that affect economic growth rather than to predict it.

An important conclusion about the use of system dynamic models is that the models must be kept as simple as possible when introducing new ideas. The complexity can be built up as each new idea is introduced.

2 Development of a physical economic model

Resources have been split into three classes; depletable, recyclable and renewable because each has significantly different physical properties. Special attention is given to energy resources because they are an essential input to the economy and most common sources currently used in the economy are depletable. There are several different forms of energy analysis and each gives different insights into physical limits.

The physical economic growth model developed in Chapter 9 emphasises the importance of technology and resource-pollution scarcity for economic growth. This analysis is significantly different from conventional economic growth models which focus on predicting human behaviour. In the long term, human behaviour cannot be predicted so it has been left out of the model. Because of this the model is much simpler and the model focuses only on the physical assumptions required for economic growth.

It is important to analyse physical causes of technological change as this is an area conventional economic growth models ignore. Learning curves are one way in which technology may be analysed. Physical factors such as energy requirements may be an important indicator of possible rates of learning in different sectors of the economy. The growth model developed in Chapter 10 includes physical influences on technological development while still recognising that investment accelerates the learning process. This is the first economic growth model (the author is aware of) that includes a physical mechanism as an explanatory factor for differences in technological trends. Although no clear conclusion can be made about the link between technological progress (learning) and energy analysis this is a most promising area for further investigation.

3 Application of a physical economic model

The ECCO methodology for analysing long term physical limits on economic growth was reviewed and was found to have several methodological deficiencies. These deficiencies have been discussed in detail and methods of improving the model have been developed. The modelling methodology developed in this thesis is an improvement on that of Slesser et al. in three significant ways. Firstly, growth in the models is based on the neoclassical idea that technology is the main driver of economic growth, rather than on classical growth theory which emphases savings as the main determinant of growth. Secondly, the numeraire used in the models is a dimensionless index of volume so the model does not assume an energy theory of value. A double set of accounts has been developed so a dynamic energy analysis of the economy runs parallel to the main set of accounts. Finally, the model is based on a full set of input-output data which enables a more accurate analysis of flows between sectors in the economy. This also makes the model much more structured so it is easy to expand the number of sectors in the model using the same set of calculations.

The energy balance of the system and the use of static input-output analysis to determine the initial conditions of the model are two new methods that help track down errors in the data and structure of the models.

Because the model is so different from the original ECCO models they have been renamed Structural Economy-Environment Simulation Models (SEESM). It is perhaps the first full input-output model to be run in a dynamic simulation environment. Thus, it has the advantage of the detailed structural information found from input-output analysis combined with the flexibility of simulation models. The resulting model is ideal for investigating the complex dynamic phenomenon of an evolving economy.

The new methodology has been applied to the global economy to illustrate the basic principles of the model. The purpose of this model is not to predict future economic growth but to highlight the physical assumptions required for any particular scenario.

Once these physical assumptions have been identified, they are open to scrutiny and can easily be changed to test their importance.

The SEESM model has been applied to the New Zealand economy and several different scenarios have been tested. The simulations include changing the overall growth rate of the economy, changing relative growth rates of different sectors, changing energy efficiencies, and introducing renewable energy technologies on a large scale. These simulations show that in some cases there are significant indirect physical flows that may not have otherwise been accounted for.

The general conclusions about physical limits on the growth of the New Zealand economy are optimistic. There appear to be no immediate physical restrictions although there needs to be more work done on some of the data for the model to be able to be taken to a firm conclusion. Part of the reason for optimism in the New Zealand economy is the quantity of productive land and renewable energy options within New Zealand.

4 Further work

Several aspects of this research could be developed further. Perhaps the most promising areas include development of a generic dynamic input-output simulation methodology and the further development of physical economic growth theory. The data used for the New Zealand simulation models could be further analysed to give better insights about future development options.

4.1 Data analysis and scenarios

The next step in the development of the model would be to spend time on developing possible scenarios. The best way to do this would be to work with interested organisations like the Ministry of Environment, Ministry of Commerce, Statistics New Zealand, business and community groups etc. One person working on their own is not in a good position to choose or decide which scenarios are best to investigate.

There are a number of sectors in the model that could easily be improved based on other people's work. For example, it would be an easy step to improve the population model to include the changing age structure of the population and how this may affect the demand from different sectors in the economy. Good population models have been included in the models of Slesser et al. (1994) and Meral et al. (1994). Once this has been done links between demand from different sectors and age groups could be included in the model. An example of this is that more health care is required by the elderly. This way, some of the effects of changing age of the population on the structure of the economy could be investigated.

Using NZSEESM general algorithms have been designed which are common to all sectors of the economy it so it will be easy to expand the model to include a 25 sector input-output data set. This would enable a much greater level of detail to be included in the scenario options. More effort could also go into estimating trends in individual sectors of the economy for energy efficiency and labour and capital requirements.

Although the model so far has concentrated solely on long term questions it may be possible to model the short term fluctuations in growth of the system. For example, high short term growth rates can lead to skills shortages and it takes time to train people. There is no reason that this type of influence could not be included in future models.

4.2 Energy analysis

A significant science has been built around the use of energy analysis and the concept of embodied energy. The dynamic model developed in this thesis is a significant advance in the methodology of estimating embodied energy and how it changes over time.

A factor that makes NZSEESM complicated is the use of constant embodied energy as a dimensionless index of volume of production. The author recommends the use of money as a numeraire as money can be used as a dimensionless index of the volume of production. It is much easier to explain and justify than the new dimensionless index of constant embodied energy. So long as money is used only as an index of volume it can successfully be used in a physical model (see chapter 13). The energy analysis that runs parallel will give an important set of indicators about physical limits in different sectors of the economy.

4.3 Dynamic input-output model

Even though the SEESM series of models are much more structured than previous ECCO models it may be possible to simplify them further. A valuable tool would be a generic dynamic input-output simulation model. This could have advantages over conventional input-output methods as it allows more flexibility and feedbacks and non-linearities can be included.

Herendeen (Brown and Herendeen, 1995) emphasises that input-output methods developed for energy analysis could be used for other inputs to the economy. The same is true of the dynamic input-output methodology. Analysis of the energy flows has been the focus in this thesis, but arguably the methodology can just as easily be used to analyse other critical physical flows such as materials or labour.

It is also recommended that the SEESM models should be converted from Dynamo to a simulation package such as Vensim which has more tools for analysing the model.

4.4 Physical economic growth theory

The economic growth model developed in Chapters 9 and 10 emphasised the importance of technological change and how it may be linked to physical flows. More effort needs to go into analysing how technology has progressed in each different sector in the economy. The relationship between technological change and the physical characteristics of the sector can also be investigated further.

5 A last word

Given the complexity of the whole issue of sustainable development, any new angle or insight to the problem is extremely valuable. The models presented in this thesis are not *the* solution to understanding economic environmental problems but another tool to give a different analytical analysis of the problem. A dynamic analysis of long term physical flows is essential for understanding development options and the model developed in this thesis is believed to be a significant advance on previous models.

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Appendix 1: Discussion of CORECCO

CORECCO is a simple world model designed by Slesser (1992) to illustrate the basic concepts of ECCO and how it models physical restrictions on growth of the world economy. CORECCO has four sectors; population, agriculture, human-made capital (industry) and natural capital acquisition. Physical limits on growth in CORECCO are caused by the increasing scarcity of productive land and the increasing scarcity of energy resources. In the energy sector (natural capital acquisition) the limit is modelled by including a table function[1] that relates the amount of capital required to retrieve energy resources, to the stock of energy resources remaining. As more energy is required, there is an increased requirement for capital and therefore there is less capital available for investment. Physical limits are modelled in a similar way. As the food demand per unit of arable land increases, capital demands in agriculture increases. Thermal energy demand also increase in the agriculture sector as the food demand per unit of arable land increases.

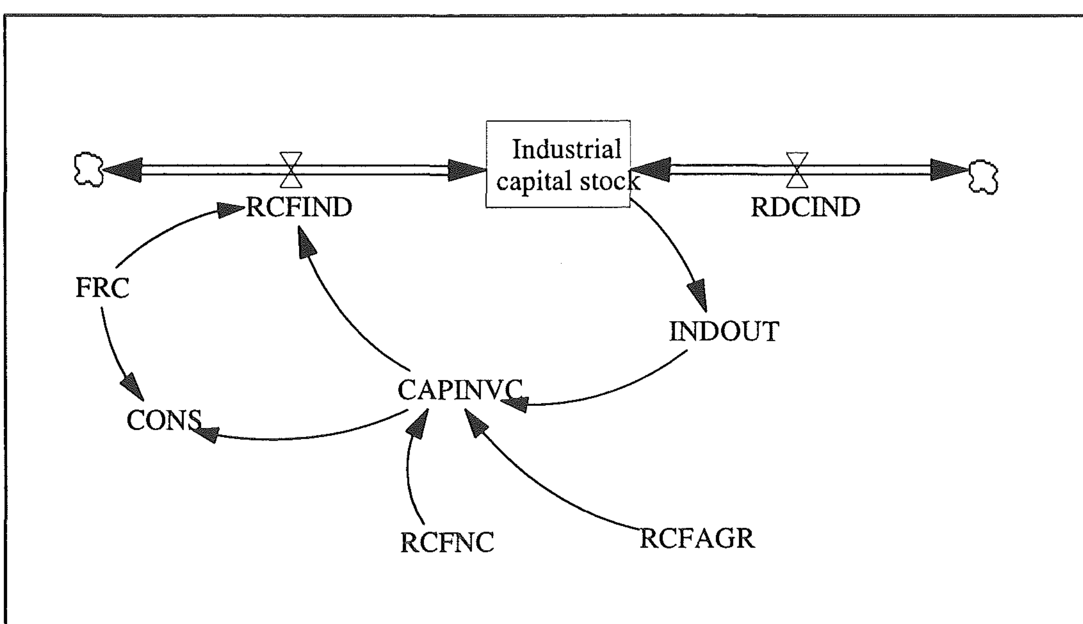

Figure A-1 Basic growth influence diagram diagram in CORECCO

Figure A-1 shows the basic structure of the model[2]. It is argued that as resources get used it takes more capital to make them available to the economy. This is the rate of capital formation in natural capital (RCFNC) increases. At the same time more capital and energy is required in the agriculture (RCFAGR) sector as more has to be produced on each unit of land. These increased capital and energy requirements mean there is less capital available for investment and consumption (CAPINVC) which causes the industrial output to decline after about the year 2000 (see Figure A-2).

To understand the relative significance of the limits in the agriculture and energy sectors, a second modified model CORECCO2 model has been produced so the results of the two models can be compared. Several slight changes are made to understand the causes of growth and decline in the CORECCO model. Each of the physical restrictions will be removed one at a time to see the relative effects of each on the long term growth of industrial output.

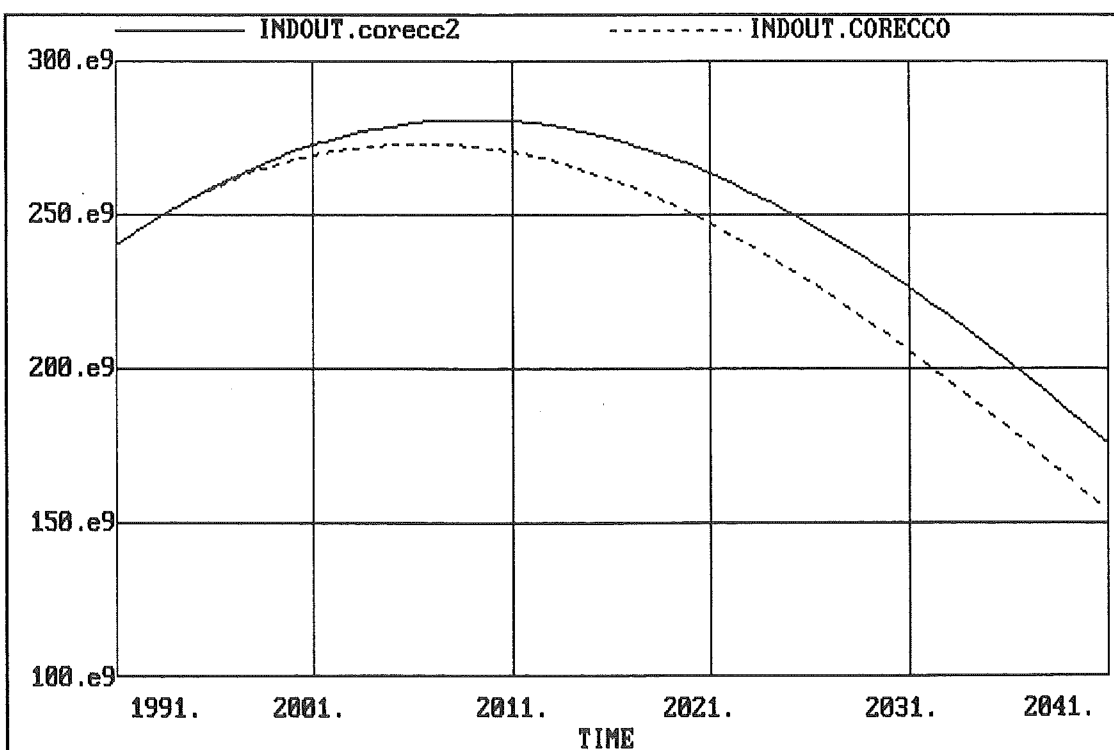

Figure A-2 CORECCO with and without the energy constraints on growth

First the physical restriction on the energy sector is removed. This is done by changing the capital requirement in the energy sector. In the new model this capital requirement is assumed to be constant rather than increasing as resources are depleted. The results of the two models are compared in Figure A-3. Industrial output is used as a comparison as this is the best indicator in ECCO of the productive capacity of the economy. The comparison shows that removing the energy constraint has only a relatively small effect on the overall growth of the economy. That is, the dominant trend of a peak followed by long term downward movement continues.

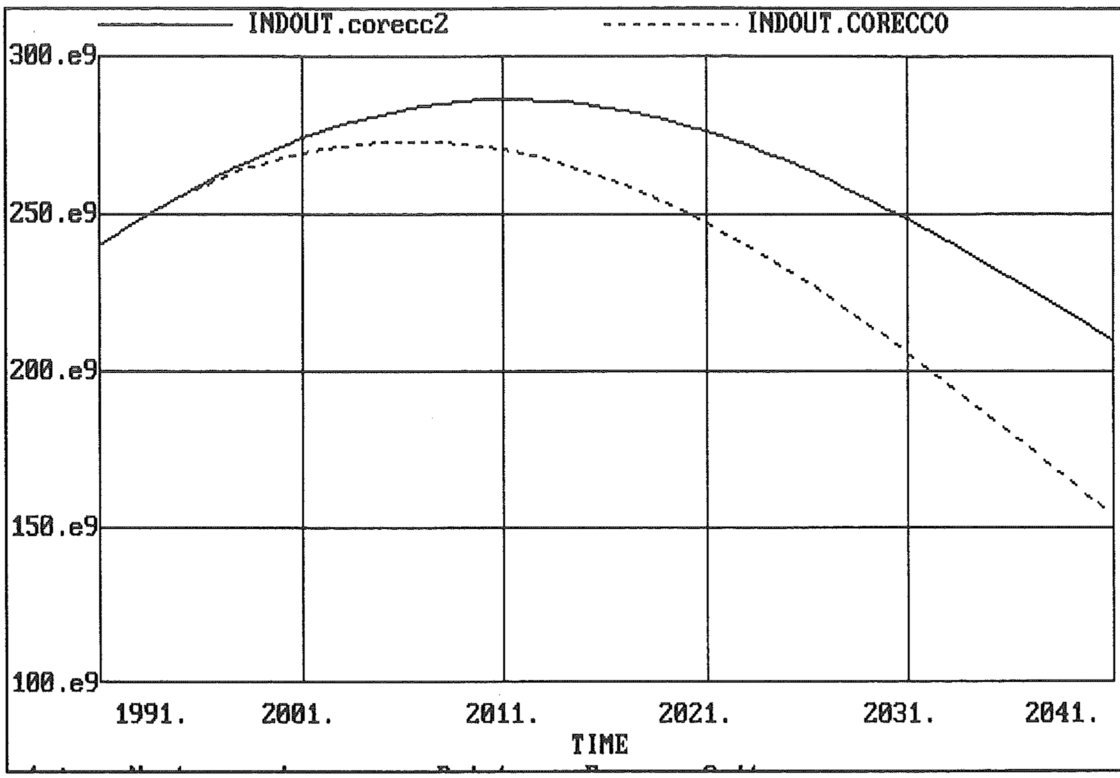

Figure A-3 CORECCO with energy and agricultural restrictions removed

The next physical restriction to be removed is in the agricultural sector. Again this is removed by assuming that the capital requirements are constant rather than increasing as the quantity of food produced per unit of land increases. The quantity of energy required per unit of land is also held constant. The results of the model without agricultural or energy restriction are compared to a simulation with the restrictions in Figure A-3. Again removing the restrictions appears to have relatively little effect on the major downward trend of industrial output.

If the physical restrictions have been removed, why does long term industrial output still fall? The reason industrial output declines when the physical restrictions are removed is that the rate of growth of the industrial sector is not as fast as the rate of growth of population. In this model, growth of population causes an increased demand for consumption goods which reduces the capital available for investment back into industry (human-made capital). This is the method Slesser uses to "close the loop" and make growth endogenous rather than exogenous[3]. However, it is difficult to justify this feedback as a physical restriction on economic growth. There are many other assumptions one could make about the allocation of industrial output between consumption and investment that would give radically different results. As argued in chapter 13 it is technological assumptions rather than allocation of industrial output that is important. An example of a slightly different method of allocating capital is shown below.

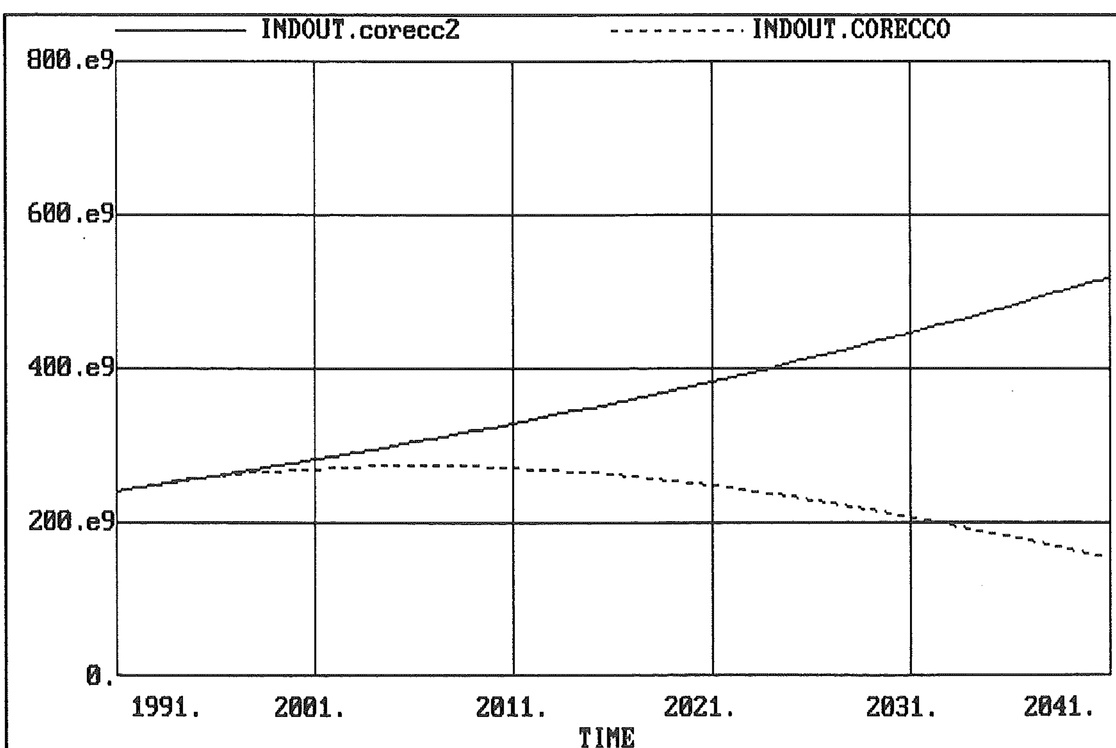

Figure A-4 CORECCO assuming investment is a fixed proportion of industrial output.

If the model is run assuming consumption is a fixed proportion of the industrial output the model will grow as in Figure A-4. Even if physical restrictions are reactivated, the model can still grow well into the next century (the result of this increased growth is that land and energy limits may be reached more quickly). One of the biggest problems with a model like ECCO is determining a realistic growth scenario, based on the social decisions between investment and consumption. As has been illustrated, one of the major determinants of the overall growth of the model is the almost arbitrary choice of how the capital is allocated between investment and consumption. The argument in chapter 13 emphasises that calculating the assumed technological improvement may be the best way to find a realistic allocation between investment and consumption. If this calculation is done in CORECCO it is found that the assumed technological improvement is negative. That is, less industrial output is being produced per person than in the past. It is very difficult to justify this assumption.

1 Equations in Corecco

The following discussion analyses the Corecco model in detail to understand the growth algorithm. The method by which Corecco is set up to grow is not immediately obvious from the program listing. A simpler method is designed to make the policy options and model easier to follow and easier to change.

In Corecco the method of allocating capital between consumption and investment is as follows:

RCFMMC = (INDOUT-RCFNC-RCFAGR)/(1+RGC) (1)

RCFMMC	Rate of capital formation in man made capital
INDOUT	Industrial output
RCFNC	Rate of capital formation in natural capital
RCFAGR	Rate of capital formation in agriculture
RGC	Rate of growth of consumption

CONS = RGC*RCFMMC (2)

CONS	Consumption
RGC	Rate of growth of consumption

RGC = RGCF*EXP((TIME.K-INITIME)*LOGN(1+(FRC/100))) (3)

RGC Rate of growth of consumption

RGCF Rate of growth of consumption factor

For simplification assume that FRG is equal to 0. Therefore, RGC equals RGCF in the following discussion.

RGCF = 5.34*POPF (4)

POPF Population factor

Another way of presenting the same equations in an easier to understand form is:

CAPINVC = INDOUT - RCFAGR - RCFNC (5)

CAPINVC	Capital available for investment or consumption
INDOUT	Industrial output
RCFAGR	Rate of capital formation in agriculture
RCFNC	Rate of capital formation in natural capital acquisition (energy)

There is no "choice" in allocating RCFAGR of RCFNC as these rates of capital formation are determined by physical requirements of the system. The capital left over (CAPINVC) can either be allocated to consumption or to investment in man-made capital. Equations 1 to 5 can be rearranged to give clearer expressions of RCFMMC and CONS.

Substitute equation 5 into equation 1

RCFMMC = CAPINVC/(1+RGC) (6)

equation 6 rearranged

RCFMMC*(1+RGC)=CAPINVC (7)

equation 2 rearranged

RGC = CONS/RCFMMC (8)

Equation 8 into 7

RCFMMC(1+(CONS/RCFMMC))=CAPINVC

simplifies to

RCFMMC+CONS=CAPINVC (9)

rearranged to

RCFMMC=CAPINVC-CONS (10)

Equation 10 into equation 2

CONS= RGC*(CAPINVC-CONS)

Simplified to

CONS(1+RGC)=RGC*CAPINVC (11)

rearranged to

CONS=CAPINVC*(RGC/(1+RGC)) (12)

Equation 4 into equation 12

CONS=CAPINVC*(5.34*POPF/(1+5.34*POPF))

simplified to

CONS = CAPINVC*(POPF/(0.1872659+POPF)) (13)

CONS	Consumption
RGC	Rate of growth of consumption
POPF	Population factor
RCFMMC	Rate of capital formation in man made capital
INDOUT	Industrial output
RCFNC	Rate of capital formation in natural capital
RCFAGR	Rate of capital formation in agriculture
RGC	Rate of growth of consumption
CAPINVC	Capital available for consumption or investment
INDOUT	Industrial output
RCFAGR	Rate of capital formation in agriculture
RCFNC	Rate of capital formation in natural capital acquisition (energy)

The two important equations that result from this are equations 13 and 10

RCFMMC = CAPINVC - CONS (10)

CONS = CAPINVC*(POPF/(0.1872659+POPF)) (13)

Expressing RCFMMC and CONS in this form clearly shows the decisions made when allocating the capital available for consumption or reinvestment. Consumption is a function of the population factor and the remaining CAPINVC is reinvested in man made capital. Equation (13) is essentially a policy decision rather than a physically determined way of allocating the capital in CORECCO. An alternative way of allocating the capital would be to assume that the consumption is a set fraction of CAPINVC.

CONS = FRCCONS * CAPINVC (14)

CONS	Consumption
FRCCONS	Fraction consumed

As the discussion in the main text emphasises any choice of allocation has an associated implied rate of technological change which may be the key limitation on economic growth.

2 Energy balance in Corecco

An energy balance is required so there is no double counting of energy flows in Corecco. The energy inputs to the economy must be equal to the embodied energy of the outputs of the economy plus the change in the energy embodied in the capital stocks. The change in the capital stocks can be calculated by the difference between the rate of capital formation and the rate of capital depletion.

ENIN = TRD GJ

ENOUT = CONS + AGROUT GJ

ENIN	Energy into the economy
TRD	Total primary energy demand
ENOUT	Energy out of the economy
CONS	Consumption
AGROUT	Agricultural output

CHCPST=(RCFNC-RDCNC)+(RCFMMD-RDCMMD)+(RCFAGR-RDCAGR) GJ

CHCPST	Change in capital stock

NENIN=ENIN-CHCPST

NENIN	Net energy into the economy

NENIN should equal ENOUT if the energy balances are correct.

CONS and AGROUT are the only outputs to final demand in Corecco. Much of the industrial output is embodied in the capital stocks in Corecco. The output from the energy sector is embodied in the other outputs through system gross energy (SYSGER).

The energy balance is not correct in Corecco as the system gross energy requirement (SYSGER) is constant. SYSGER is the amount of energy required to make the energy resources available. In this example the energy required to make the energy resources available is the energy embodied in the capital of the energy sector. The calculation for SYSGER is:

SYSGER.K= (TRD+RDCNC)/TRD

SYSGER	System gross energy requirement
TRD	Total thermal energy demand
RDCND	Rate of capital depletion in natural capital sector

All of the changes mentioned above are included in the Globe series of models and the energy balances are correct. Monitoring the energy balances after making changes to the model is an excellent method of ensuring "correct" accounting of the energy flows.

1. A table function in DYNAMO allows two variable to be linked by an exogenously determined table of data. In this case the capital required to access energy increases as a function of the cumulative depletion of the energy resources.

2. The equations are slightly modified to make the growth algorithm easier to follow (see below).

3. Slesser does note that his method is not the only method of closing the loop, however, it is not made clear what a huge significance this feedback has on the model or how uncertain this feedback is.

Appendix 2: Input-output analysis

The finite difference equations used to simulate the economy require initial conditions (see Pugh, 1991). That is, the embodied energy of outputs in all sectors must be supplied as initial conditions and they can be found using input-output analysis. From these initial conditions the dynamic method of calculating embodied energy described in Appendix 5 can be used.

There has been much work on the analysis of input-output tables to find energy requirements for different sectors in the economy and the matrix methods of analysing are well documented (Peet, 1991a, 1993b). The outputs of each sector in embodied fossil energy calculated from a static matrix analysis are shown in the table below (1981-82 data). This data is used in the New Zealand model as the initial conditions and is an excellent check that the data and structure of the model are accurate. This enables errors to be traced (see Chapter 15).

Sector	Output (GJ)
Industry	354,358e3
Transport	71,640e3
Services	147,748e3
Life support	84,012e3
Electricity	49,194e3
Thermal fuels	100,576e3

Table 1 Initial conditions

The initial conditions from static analysis are not exactly the same as those found from the dynamic ECCO style analysis because the energy embodied in capital stocks are not included in the input-output matrix analysis. These differences are quite small so large errors caused by incorrect data or structure will still be obvious.

A dynamic input-output analysis has advantages over static input output analysis in that any relationships between variables can change. For example, inputs to each sector are assumed to be a simple proportion of the level of output of that sector (Peet 1991a). In the dynamic model these proportion can change (eg energy efficiencies).

The tables on the following two pages shows the input-output data used in the UKECCO (Slesser et al. 1994) and the New Zealand DIOC models (see Appendix 5 for a list of the acronyms. Where ever there is a zero the transaction is not included in the model. Comparison of the two tables show how much more detailed the New Zealand model is.

	Industry	Transport	Market services	Non-market ser	Water	Electricity	Fuels	Agr	Fishing	Final demand
Industry	RCFIND	RCFTRA	RCFMKS	RCFNMS	RCFWAT	RCFEL	RCFTED	RCFAGR	RCFFISH	CONS
Transport	ITRAOUT	0	LGV	LGV	0	0	0	0	0	PRIV + BUS..
Market services	MKISOUT	0	MKSSOUT	MKSSOUT	0	0	0	0	0	MKPSOUT
Non-market services	0	0	0	0	0	0	0	0	0	NMSOUT
Water	WATIND	0	0	0	0	0	0	0		WATMAIN
Electricity	EEDIND	EEDTRA	EEDMKS	EEDNMS	EEDWAT	EEDELEC	EEDREF	EEDAG	EEDFISH	EEDDOM
Thermal fuels	TEDIND	TEDTRA	TEDMKS	TEDNMS	TEDWAT	OILEL	TEDGOC	TEDAG	TEDFISH	TEDDOM
Agriculture	AGRIN	0	0	0	0	0	0	FEEDS	0	OUTAG
Fishing	0	0	0	0	0	0	0	0	0	FISHSUP
Primary inputs	IMPINT	0	NMKSXP$	NNMSXP$	0	U235IMP...	OILIMP	IMPAG	0	IMPCON

Table 2 Input-output table used in the UKECCO model. Note the number of entries that are assumed to be zero compared to the input-output table used in the New Zealand model on the next page.

	Thermal fuels	Electricity	Life support	Industry	Transport	Services	Domestic	Export	Capital formation
Thermal fuels	TEDTF	TEDEL	TEDLS	TEDIND	TEDTRA	TEDSER	TEDDOM	TEDEXP	0
Electricity	EEDTF	EEDEL	EEDLS	EEDIND	EEDTRA	EEDSER	EEDDOM	0	0
Life support	LS2TF	LS2EL	LS2LS	LS2IND	LS2TRA	LS2SER	LS2DOM	LS2EXP	LS2GCF
Industry	IN2TF	IN2EL	IN2LD	IN2IN	IN2TRA	IN2SER	CONS	NECEXG	IN2GCF
Transport	TR2TF	TR2EL	TR2LS	TR2IND	TR2TRA	TR2SER	TR2DOM	TR2EXP	TR2GCF
Services	SR2TF	SR2EL	SR2LS	SR2IND	SR2TRA	SR2SER	SR2DOM	SR2EXP	SR2GCF
Imports	IM2TF	IM2EL	IM2LS	IM2IND	IM2TRA	IM2SER	IM2DOM	0	IM2GCF
Capital formation	RCFTF	RCFEL	RCFLS	RCFIND	RCFTRA	RCFSER	RCFDOM	0	0

Table 3 Input-output table used in NZDIOC.

Appendix 3: Solving simultaneous equations in Professional Dynamo[1]

A simple model is developed to illustrate the problem of calculating the total energy requirements for different sectors of the economy. An economy with only two sectors is used to illustrate the problem. This economy has an agricultural sector and industrial sector.

The direct energy demand of industry is 100 GJ. The direct energy demand of the agriculture sector is 80 GJ. Fifty percent of agricultural output is consumed and the rest is an input to the industry sector. Ninety percent of industrial output is consumed and 10% is an input to the agriculture sector. In a real economy this information is found from input output analysis. The total embodied energy requirements of industry and agriculture are as follows.

INDOUT = 100 + 0.5*AGROUT	GJ	A1
AGROUT = 80 + 0.1*INDOUT	GJ	A2

This is an obvious simultaneous equation. As a static problem these simultaneous equations are easily solved. Similarly an entire economy's input/output can be analysed and solved using standard matrix methods (Peet, 1991). The solution in this case is:

INDOUT = 147.37	GJ
AGROUT = 94.74	GJ

The total embodied energy of output is 147.37 GJ for industry and 94.74 for agriculture. A simple balance checks the inputs are equal to the outputs.

The energy input is 100 + 80 = 180 GJ

The embodied energy output (consumption) = 0.9*INDOUT + 0.5*AGROUT = 180 GJ

How can the simultaneous equations be solved in a dynamic simulation model? That is, how can the equations be solved if values within the equation are changing over time? It is possible that industrial output and agricultural output are changing at different rates.

If equations A1 and A2 are written in DYNAMO a simultaneous equation error will occur. Dynamo has no inbuilt method of solving these simultaneous equations. A suggested method of solving these equations within DYNAMO is to use level equations (Slesser, 1992, p57). This method suggests INDOUT could now be written as:

L INDOUT.K=INDOUT.J+DT*(RF.JK-RD.JK)	Level equation	A3
N INDOUT=147.36	Initial condition	A4
R RF.KL=(100 + 0.5*AGROUT)	Rate equation	A5
R RD.KL=INDOUT	Rate equation	A6

The equation for RF.KL is exactly the same as equation A1. The level equation can be read as follows: INDOUT at time K is INDOUT at time J plus DT times the difference between the new INDOUT (RF.KL) and the old INDOUT (RD.KL). Put simply, this method allows values of the previous time interval to be used to calculate INDOUT of the present time, thus avoiding simultaneous equations. The same method can be used to calculate AGROUT. There are obvious problems with this method of calculation. If the outputs are growing then the calculated embodied energy outputs will always lag behind. As an example, the growth rate can be set at 2%. The results from the dynamo simulation can be easily compared to the expected results. The expected result would be a 2% increase in the embodied energy of INDOUT per year.

Year	0	1	2	3	4
INDOUT expected	147.37	150.32	153.32	156.39	159.52
INDOUT simulated	147.37	147.37	149.37	152.21	155.21

Table 1 - Rate of growth constant, unmodified simulation

Clearly this is not an accurate enough result. Because of the method of calculating INDOUT, the simulation lags behind what would be expected. The cumulative effect of this in the long run will lead to large errors.

Equations A3 to A6 can be modified to improve the accuracy of the simulation. RF.KL can be multiplied by the growth rate of industry so that the error from using results from a previous time interval will be smaller.

L INDOUT.K=INDOUT.J+DT*(RF.JK-RD.JK)	A3
N INDOUT=147.36	A4
R RF.KL=(100 + 0.5*AGROUT)*GRIND	A7
R RD.KL=INDOUT	A6

GRIND is the growth rate of industry - in this case 2%. The results of this simulation are shown in table 2

Year	0	1	2	3	4
INDOUT expected	147.37	150.32	153.32	156.39	159.52
INDOUT simulated modified	147.37	150.32	153.32	156.39	159.52

Table 2 - Rate of growth is constant at 2%. INDOUT simulation is modified as equation A7

This method shows that the simulated results are exactly the same as one would expect. One would expect this method of solving simultaneous equations to be correct if the growth rate is constant over time. A test of the robustness of this method is to see how well it works if the growth rate changes over time. To test this assume that the growth rate changes from 0 to 4% over ten years then back to 0% after another ten years. The results of this simulation are shown in 5 year intervals (Table 3). The results from the unmodified simultaneous equation method are also shown as a comparison.

Year	0	5	10	15	20
INDOUT expected	147.37	172.49	183.08	190.51	218.7
INDOUT simulated modified	147.37	172.49	183.08	190.51	218.7
INDOUT simulated unmodified	147.37	166.62	181.72	186.7	208.63

Table 3 - Rate of growth of the system changes

This demonstration confirms that the method of solving simultaneous equations dynamically is robust for changes in growth rates of the sorts that one would expect in an economic system. The unmodified method of solving simultaneous equation has an unacceptably large errors.

The method of solving simultaneous equations in the ECCO models is similar to that described here. The initial conditions need to be found from solving the set of simultaneous equations outside DYNAMO. The simultaneous equations within DYNAMO are solved by using past values multiplied by the expected growth rate over that interval. This is not a perfect method of solving a dynamic series of simultaneous equations but is considered sufficient for the imprecise nature of the data and problem.

Notes

1. Professional Dynamo is a dynamic simulation software tool (Pugh, 1991)

Appendix 4: Data sources for NZSEESM

This Appendix outlines where data for NZSEESM were found. Other significant information such as the input-output sector break down are also explicitly defined. Unless other wise stated the data are from New Zealand Official Year books.

1 Input-output data

NZDIOC is split into six sectors. The definitions below show the subsection within each of the main sectors. The number in brackets refers to the industry category number as defined by Department of Statistics (1986)

Industry includes:

slaughtering and preserving meat	(11)
dairy products	(12)
other food preparations	(13)
beverage and tobacco products	(14)
textiles	(15)
apparel and footwear	(16)
wood and wood products	(17)
paper	(18)
printing and publishing	(19)
industrial chemicals	(20)
other chemicals	(21)
Petroleum and coal products	(23)
rubber products	(24)
plastic products	(24)
Non-metallic minerals	(26)
iron and steel products	(27)
Nonferrous metals	(28)
fabricated metal products	(29)

machinery nec	(30)
electrical machinery	(31)
transport equipment	(32)
professional equipment	(33)
other manufacturing	(34)
construction industries	(38,39)

Transport includes:

rail transport	(42)
road passenger transport	(43)
road and freight transport	(44)
water transport	(45)
air transport	(46)

Services include:

Agricultural services	(4)
wholesale and retail trade	(40)
restaurants and hotels	(41)
services to transport	(47)
communication	(48)
banking, financial and services	(49,50)
insurance	(51)
ownership and leasing of real estate	(52)
business services	(54)
public administration and defence	(55)
sanitary and cleaning services	(56)
education	(57)
social and related community services	(58)
health services	(59)
recreational and cultural services	(60)
personal services	(61)
domestic services of households	(62)

Thermal fuels sector includes:

coal mining	(8)
crude and natural gas	(9)
petroleum refining	(22)
gas man and distribution	(36)

Electricity sector includes:

electricity	(35)

Life support systems include:

dairy farming	(1)
sheep and beef farming	(2)
other farming	(3)
hunting and trapping	(5)
forestry and logging	(6)
fishing	(7)
water works and supply	(37)

2 Capital stock data

Capital stocks for NZDIOC are based on the data from Philpott (1989). Measured in billions 1982 New Zealand dollars.

Industry	
Wood	0.880
Paper	1.974
Machinery	2.731
Construction	2.148
Food	4.549
Textiles	1.015
Non metal minerals	0.647

Basic Metals	0.845
Chemicals	0.434
Mining in general	1
Total	16.223
Services	
Trade	9.232
Communication	2.242
Finance	9.270
Government services	21.48
Community and personal	2.456
Total	44.681
Transport and storage	8.416
Dwellings	40.405
Life support systems	
Agriculture	22.624
Fisheries	0.13
Forestry and logging	0.722
Water	2
Total	25.476
Fossil fuels	
Coal mining etc.	1.122
Gas	1.6
Oil refining	1.2
Total	3.922
Electricity	8.86

3 Other data

The life times of the capital stocks were found by comparing the estimated capital stock to the known rates of capital formation and growth of the sector. The life time of capital stock was adjusted until the rate of capital formation equalled what it actually was.

Carbon dioxide emission figures are taken from Slesser et al. (1994)

Data on energy use in the New Zealand economy comes from Energy Data Files and the input output data (see table in Chapter 15).

Appendix 5: Partial listing of NZSEESM

The important sections of NZSEESM is listed below alone with a brief description of the logic behind program listing. A full listing is on the accompanying disk.

NZBASE.DYN is a six sector New Zealand SEESM model

This is a business as usual scenario for the New Zealand econmy as described in Chapter 15

This model simultaneously keeps track of embodied fossil energy (GJ) and constant embodied energy (GJ82). The constant embodied energy is the equivalent amount of energy that would have been required in the year of the models initiation - in this case 1982. The constant embodied energy (GJ82) is then a dimensionless index of the volume of production.

1 Abbriveartions used in the model

A prefix of F to any of the above mean fossil embodied energy. This is the actual fossil energy required for outputs and capital stocks. This is measured in GJ. The equivalent embodied energy is measured in 1982 GJ (GJ82)

Gossary of terms

CS... = Capital stock of ... (giga joules, GJ)

LT... = Life time of capital stock (years, yr)

RCF... = Rate of capital formation (GJ/yr)

RDC... = Rate of capital depletion (GJ/yr)

EED... = Electricity demand (kilowatt hours per year, kWh/yr)

TED... = Thermal energy demand (GJ/yr)

LAB... = Labour requirements (Labour, L)

...OUT = Output of the sector (GJ/yr)

IND or IN = Industry
SER or SR = Services non-market
TRA or TR = Transport
DOM or DM = Domestic sector
TF = Thermal fuels
EL = Electricity
EXP or EX = Exports
IMP or IM = Imports
GCF or GC = Gross capital formation
PER or PR = Final demand

An example of the acroynms is TRA2IN = the amount of transport (TRA) that goes to (2) industry (IN). This is mearured in the dimensionless index (GJ82).

2 Key macros used in NZSEESM

2.1 Calaculating capital stock

This macros calculates the capital stock and rates of captial formation and depletion from an initial capital stock and a desired capital stock.

MACRO[1] CAPSTK(INTCS,LTCS,DCS,RCF,RDC)
NOTE INTCS Initial capital stock (1982 $)
LTCS Life time of capital stock (years)
DCS Desired capital stock
DCF Delay in capital formation (years)
RCF Rate of capital formation
RDC Rate of capital formation
EII Energy intensity of capital GJ/$
INTRN RCF1

L CAPSTK.K=CAPSTK.J+DT*(RCF.JK-RDC.JK) Capital stock (GJ82)

N CAPSTK=INTCS*EII Initial capital stock (GJ82)

R RCF.KL=MAX(RCF1.K,0) Max function ensures RCF is positive

A RCF1.K=DCS.K-CAPSTK.K+RDC.K Rate of capital formation (GJ82)

R RDC.KL=CAPSTK.K/LTCS.K Rate of capital depletion (GJ82)

MEND This just means the end of a macro

2.2 Calculating capital stock in embodined fossil energy

MACRO FCAPSTK(INTCS,RCFY,LTCS,FRCF,FRDC)

NOTE This macro calculates the CS in terms of embodied fossil energy

Prefix (F) stands for fossil energy

This macro calculates the capital stock in actual embodied fossil energy

FCAPINV Available capital for investment (GJ embodied fossil energy)

L FCAPSTK.K=FCAPSTK.J+DT*(FRCF.JK-FRDC.JK) CS in embodied fossil energy

N FCAPSTK=INTCS*EII

R FRCF.KL=RCFY.K*(FCAPINV.K/CAPINV.K)

Grows at same relative rate as RCF above

R FRDC.KL=FCAPSTK.K/LTCS.K

MEND

2.3 Calculating direct energy demands

This macro calculates the output of the sector in terms of GJ82

MACRO

OUTPUT1(CS,RDC,RTED,REED,TED,EED,FOUTPT1,FRDC,EFTH,EFEL,
FRDADJ)

(OUTPUT) and in terms of embodied fossil energy (FOUTPUT)

RTED Required thermal energy (GJ per yr in 1982)

REED Required electrical energy (kWhr per yr in 1982)

EFTH Efficiency of thermal energy use (GJ/GJ in 1982)

EFEL Efficiency of electricity use (kWhr/kWhr in 1982)

LTCS Life time of capital stock

```
INTRN CSF,NCS
A  OUTPUT1.K = RDC.KL+((TED.K/EFTH.K)*FERTFN)+((EED.K/EFEL.K)
             *FERELN)       Output (GJ82)
A FOUTPT1.K=FRDC.KL+FRDADJ.KL+(TED.K*FERTF.K)+(EED.K*FEREL.K)
                            Output (GJ)
A TED.K=CSF.K*RTED.K*EFTH.K   Thermal energy demand  (GJ/yr)
A EED.K=CSF.K*REED.K*EFEL.K    Electrical energy demand  (kWhrs/yr)
N NCS=CS                      Initial capital stock
A CSF.K=CS.K/NCS              Capital stock factor
MEND
```

2.4 Calculating indirect energy inputs

This macro calculates the total output of the sector

```
MACRO OUTPUT(NOUTPUT,INTFRC,OUTPT1,INPTS,GRX,^
        FOTPUT,FOUTPT1,FINPTS)
  INTFRC          Internal requirement for output (fraction)
  NOUTPUT         Initial output (GJ82) this is from Input-output data
  OUTPUT1         Direct energy requirement for output (GJ82)
  INPTS           Indirect inputs to the sector (GJ82)
  GRX             Growth rate of the sector (avoid simultaneous equations lag)
  FOUTPUT         Fossil output (GJ)
  FOUTPUT1        Direct fossil energy requirements (GJ)
  FINPTS          Indirect fossil inputs to the sector (GJ)
INTRN RFZ,RDZ,RFZF,RDZF,OTPUT2,FOTPT2
A OTPUT2.K=OUTPT1.K+INPTS.K
L OUTPUT.K=OUTPUT.J+DT*(RFZ.JK-RDZ.JK)
N OUTPUT=NOUTPUT
```

```
R RFZ.KL=(OTPUT2.K/(1-INTFRC))*((GRX)+1)
R RDZ.KL=OUTPUT.K

A FOTPT2.K=FOUTPT1.K+FINPTS
L FOTPUT.K=FOTPUT.J+DT*(RFZF.JK-RDZF.JK)
N FOTPUT=NOUTPUT
R RFZF.KL=(FOTPT2.K/(1-INTFRC))*(GRX+1)
R RDZF.KL=FOTPUT.K
MEND
```

2.5 Calculating the adjusted capital stock

Calculates the adjusted (extra) capital stock required for increased thermal and electrical efficiency as well as for increasing labour productivity

```
MACRO ADJCS(RFEFTH,RFEFEL,RFLP,LTADJ,RFAJCS,RDAJCS,FADJCS,
      FRFAJCS, FRDAJCS)
  RFEFTH          extra capital required to increase the thermal efficiency
  RFEFEL          extra capital required to increase the electrical efficiency
  RFLP            extra capital required to increase labour productivity
INTRN FRCAJCS
L ADJCS.K=ADJCS.J+DT*(RFAJCS.JK-RDAJCS.JK)   Adjusted capital stock
N ADJCS=0
R RFAJCS.KL=RFEFTH.K+RFEFEL.K+RFLP.K
R RDAJCS.KL=ADJCS.K/LTADJ.K

L FADJCS.K=FADJCS.J+DT*(FRFAJCS.JK-FRDAJCS.JK)
                    Adjusted capital stock GJ
N FADJCS=ADJCS
R FRFAJCS.KL=FRCAJCS.K*FCAPINV.K
R FRDAJCS.KL=FADJCS.K/LTADJ.K
A FRCAJCS.K=RFAJCS.KL/CAPINV.K
```

Fraction of capital invested in adjusted capital stock

MEND

2.6 Calculating the growth rates of each sector of the economy

This macro calculates the growth rates of each sector in the economy.

```
MACRO DGR(NFA,NFB,NFC,NFD,NFE,NFF,NFG,NFH,NFI,TNFRA^
          ,DGRA,DGRB,DGRC,DGRD,DGRE,DGRF,DGRG,DGRH,DGRI,^
            FA,FB,FC,FD,FE,FF,FG,FH,FI,TFRA)
  DGR       Desired growth rate of the sector
  NFA       Initial amount of fraction of sector A to this sector
  DGRA      Desired growth rate of sector A
  FA        Fraction of output to sector A
NOTE  This macro calculates the desired growth rate of a sector
INTRN GRA1,GRB1,GRC1,GRD1,GRE1,GRF1,GRG1,GRH1,GRI1,^
     RFA1,RFB1,RFC1,RFD1,RFE1,RFF1,RFG1,RFH1,RFI1,^
     RDA1,RDB1,RDC1,RDD1,RDE1,RDF1,RDG1,RDH1,RDI1
A DGR.K=GRA1.K+GRB1.K+GRC1.K+GRD1.K+GRE1.K+GRF1.K+
        GRG1.K+GRH1.K+GRI1.K
A GRA1.K=(1+DGRA.K)*FA
A GRB1.K=(1+DGRB.K)*FB
A GRC1.K=(1+DGRC.K)*FC
A GRD1.K=(1+DGRD.K)*FD
A GRE1.K=(1+DGRE.K)*FE
A GRF1.K=(1+DGRF.K)*FF
A GRG1.K=(1+DGRG.K)*FG
A GRH1.K=(1+DGRH.K)*FH
A GRI1.K=(1+DGRI.K)*FI

A TNFRA.K=NFA+NFB+NFC+NFD+NFE+NFF+NFG+NFH+NFI
A TFRA.K=FA.K+FB.K+FC.K+FD.K+FE.K+FF.K+FG.K+FH.K+FI.K
```

```
L FA.K=FA.J+DT*(RFA1.JK-RDA1.JK)
N FA=NFA
R RFA1.KL=(GRA1.K/DGR.K)
R RDA1.KL=FA.K

L FB.K=FB.J+DT*(RFB1.JK-RDB1.JK)
N FB=NFB
R RFB1.KL=GRB1.K/DGR.K
R RDB1.KL=FB.K

L FC.K=FC.J+DT*(RFC1.JK-RDC1.JK)
N FC=NFC
R RFC1.KL=GRC1.K/DGR.K
R RDC1.KL=FC.K

L FD.K=FD.J+DT*(RFD1.JK-RDD1.JK)
N FD=NFD
R RFD1.KL=GRD1.K/DGR.K
R RDD1.KL=FD.K

L FE.K=FE.J+DT*(RFE1.JK-RDE1.JK)
N FE=NFE
R RFE1.KL=GRE1.K/DGR.K
R RDE1.KL=FE.K

L FF.K=FF.J+DT*(RFF1.JK-RDF1.JK)
N FF=NFF
R RFF1.KL=GRF1.K/DGR.K
R RDF1.KL=FF.K

L FG.K=FG.J+DT*(RFG1.JK-RDG1.JK)
N FG=NFG
```

```
R RFG1.KL=GRG1.K/DGR.K
R RDG1.KL=FG.K

L FH.K=FH.J+DT*(RFH1.JK-RDH1.JK)
N FH=NFH
R RFH1.KL=GRH1.K/DGR.K
R RDH1.KL=FH.K

L FI.K=FI.J+DT*(RFI1.JK-RDI1.JK)
N FI=NFI
R RFI1.KL=GRI1.K/DGR.K
R RDI1.KL=FI.K
MEND
```

2.7 Calculates the flows in the economy

This macro calculates where the output of each sector of the economy goes.

```
MACRO OUT1(F1,F2,F3,F4,F5,F6,F7,F8,F9,^
   OTPUT,FOTPUT,OUT2,OUT3,OUT4,OUT5,OUT6,OUT7,OUT8,OUT9,^
   FOUT1,FOUT2,FOUT3,FOUT4,FOUT5,FOUT6,FOUT7,FOUT8,FOUT9)
A OUT1.K=F1.K*OTPUT.K
A OUT2.K=F2.K*OTPUT.K
A OUT3.K=F3.K*OTPUT.K
A OUT4.K=F4.K*OTPUT.K
A OUT5.K=F5.K*OTPUT.K
A OUT6.K=F6.K*OTPUT.K
A OUT7.K=F7.K*OTPUT.K
A OUT8.K=F8.K*OTPUT.K
A OUT9.K=F9.K*OTPUT.K

A FOUT1.K=F1.K*FOTPUT.K
```

```
A FOUT2.K=F2.K*FOTPUT.K
A FOUT3.K=F3.K*FOTPUT.K
A FOUT4.K=F4.K*FOTPUT.K
A FOUT5.K=F5.K*FOTPUT.K
A FOUT6.K=F6.K*FOTPUT.K
A FOUT7.K=F7.K*FOTPUT.K
A FOUT8.K=F8.K*FOTPUT.K
A FOUT9.K=F9.K*FOTPUT.K
MEND
```

2.8 Calculating growth rates

This macro calculates the growth rate of the sector from the capital stock, rate of capital formation and rate of capital depletion.

```
MACRO GR(GRN,RFGR,RDGR,CS)
INTRN RFGR1,RDGR1
L GR.K=GR.J+DT*(RFGR1.JK-RDGR1.JK)
N GR=GRN
R RFGR1.KL=(RFGR.KL-RDGR.KL)/CS
R RDGR1.KL=GR.K
MEND
```

2.9 Calculating labour productivity

```
MACRO LAB(NLAB,RCLPS,CSS,OUTS,LP)
   RCLPS  Rate of change of labour productivity
INTRN NCS,RCLP,NLP,CSF,LPF
A LAB.K=NLAB*CSF.K*LPF.K          Labour requirements of a sertor
A CSF.K=CSS.K/NCS                 Capital stock factor
N NCS=CSS
A LPF.K=LP.K/NLP                  Labour productivity factor
```

N NLP=OUTS/NLAB

L LP.K=LP.K+DT*(-RCLP.JK) Labour productivity

N LP=NLP

R RCLP.KL=LP.K*RCLPS.K

MEND

2.10 Calculating imports

This macro calculates the imports to each sector based on the initial imports and the growth rate of the sector.

MACRO IM2SEC(NIM2SEC,GRIM,FIM2SEC)

INTRN RFIM1,RDIM1

L IM2SEC.K=IM2SEC.J+DT*(RFIM1.JK-RDIM1.JK)

N IM2SEC=NIM2SEC*EIIMP

R RFIM1.KL=IM2SEC.K*(1+GRIM)

R RDIM1.KL=IM2SEC.K

A FIM2SEC.K=IM2SEC.K

MEND

3 Example of data and calcuations in each sector

List of initial conditions

N NCSIND=16.226E9	Initial capital stock - industry ($NZ 1982)
N DIND=8	Delay in construction - industry (yr)
N LTIND=13	Life time of capital stock - industry (yr)
N INDTED=6.4621e7	Thermal energy demand - industry (GJ/yr)
N INDEED=7.719784e9	Electricity demand - industry (kWh/yr)
N GRIND=NGR	Initial growth rate - industry
N NINDOUT=320E6	Initial industrial output (GJ)
N INDOUT$=32.16e9	Initial industrial output ($)
N EII=NEIIND	Energy intensity of capital (GJ/$)

N NLABIND=381100	Initial labour in industry (L)

N NIN2PRF=0.1586	Fraction of industrial output to cons or invest
N NIN2SRF=0.0902	Fraction of industrial output to services
N NIN2INF=0.3420	Fraction of industrial output to industry
N NIN2TRF=0.0176	Fraction of industrial output to transport
N NIN2TFF=0.0025	Fraction of industrial output to thermal energy
N NIN2ELF=0.0007	Fraction of industrial output to electricity
N NIN2LSF=0.0588	Fraction of industrial output to life support
N NIN2EXF=0.1772	Fraction of industrial output to export
N NIN2GCF=0.1523	Fraction of industrial output to capital formation

Future conditions

A EFTHIND.K=GENTEFF.K	Thermal energy efficiency industry
A EFELIND.K=GENEEFF.K	Electricity efficiency industry
A RFTHIND.K=GENCPTH.K*RCFIND.KL	Extra capital required for thermal efficiency
A RFELIND.K=GENCPEL.K*RCFIND.KL	Extra capital required for electric efficiency
A RFLPIND.K=GENCPLP.K*RCFIND.KL	Extra capital required to increase labour productivity

Desired growth rates

A GRIN2PR.K=GRPER.K	Growth rate of industry to final demand
A GRIN2SR.K=GRSER.K	Growth rate of industry to services
A GRIN2ND.K=GRIND.K	Growth rate of industry to industry
A GRIN2TR.K=GRTRA.K	Growth rate of industry to transport
A GRIN2TF.K=GRTFX.K	Growth rate of industry to thermal fuels
A GRIN2EL.K=GREL.K	Growth rate of industry to electricity
A GRIN2LS.K=GRLS.K	Growth rate of industry to life support
A GRIN2EX.K=GREXP.K	Growth rate of industry to exports

A GRIN2GC.K=GRIN2X.K Growth rate of industry to gross capital formation

Calculations common to each sector in the economy. Each of the macros outlines above are called in each sector of the economy.

A CSIND.K=CAPSTK(NCSIND,LTIND,DCSIND.K,RCFIND.KL,DCIND.KL)
Capital stock and rates of capital formation and depletion (GJ82)
A DCSIND.K=CSIND.K*DGRIND.K Desired capital stock - industry
A AJCSIND.K=ADJCS(RFTHIND.K,RFELIND.K,RFLPIND.K,LTIND,
RFAJIND.KL,RDAJIND.KL,FAJCSND.K,FRFAJND.KL,FRDAJND.KL)
Extra capital required for increasing electricity and thermal fuel efficiency and labour productivity
A FCSIND.K=FCAPSTK(NCSIND,RCFIND.KL,LTIND,FRCFIND.KL,
FRDCIND.KL)
Capital stock and rates of capital formation and depletion (GJ)
A INDOUT1.K=OUTPUT1(CSIND.K,RDCIND.KL,INDTED,INDEED,
TEDIND.K,EEDIND.K,FINDOT1.K,FRDCIND.KL,EFTHIND.K,
EFELIND.K,FRDAJND.KL) Electricity and thermal energy demands
A INDOUT.K=OUTPUT(NINDOUT,IN2INDF.K,INDOUT1.K,INPIND.K,
GRIND.K,FINDOUT.K,FINDOT1.K,FINPIND.K)
Calculation of output (GJ/Y & GJ82/Y)
A INPIND.K=SR2IND.K+TR2IND.K+LS2IND.K+IM2IND.K
Inputs to industry (GJ82/Y)
A FINPIND.K=FLS2IND.K+FSR2IND.K+FTR2IND.K+FIM2IND.K
Inputs to industry (GJ/Y)
A DGRIND.K=DGR(NIN2PRF,NIN2SRF,NIN2INF,NIN2TRF,NIN2TFF,
NIN2ELF,NIN2LSF,NIN2EXF,NIN2GCF,NTFRIND.K,GRIN2PR.K,
GRIN2SR.K,GRIN2ND.K,GRIN2TR.K,GRIN2TF.K,GRIN2EL.K,
GRIN2LS.K, GRIN2EX.K,GRIN2GC.K,IN2PERF.K,IN2SERF.K,IN2INDF.K,
IN2TRAF.K,IN2TFF.K,IN2ELF.K,IN2LSF.K,IN2EXPF.K,IN2GCFF.K,
TFRIND.K)
Calculation of the fractions of industry to other sectors and the

desired growth rate of industry

A IN2PER.K=OUT1(IN2PERF.K,IN2SERF.K,IN2INDF.K,IN2TRAF.K,
IN2TFF.K,IN2ELF.K,IN2LSF.K,IN2EXPF.K,IN2GCFF.K,INDOUT.K,
FINDOUT.K,IN2SER.K,IN2IND.K,IN2TRA.K,IN2TF.K,IN2EL.K,IN2LS.K,
IN2EXP.K,IN2GCF.K,FIN2PER.K,FIN2SER.K,FIN2IND.K,FIN2TRA.K,
FIN2TF.K,FIN2EL.K,FIN2LS.K,FIN2EXP.K,FIN2GCF.K)

Calculation of industrial output to other sectors of the economy
(GJ82 & GJ)

A GRIND.K=GR(GRIND,RCFIND.KL,RDCIND.KL,CSIND.K) Growth rate of industry

4 Material standard of living

MSOL gives an indication of the physical flow material goods and services to final demand.

A MSOLF.K=MSOL.K/MSOL82

N MSOL82=MSOL

A MSOL.K = (CONS.K+DOMOUT.K+TR2PER.K+SR2PER.K+LS2PER.K)/
POP.K (GJ82) goods per person

A MSOLF$.K=MSOL$.K/MSOL$82

N MSOL$82=MSOL$

A MSOL$.K=(GDP.K-TOTEXP$.K)/POP.K $ worth of goods per person

This assumes the same relative value of goods as in 1982

A GDP.K=(((CONS.K+DOMOUT.K)/NEIIND)+(TR2PER.K/NEITRA)+
(SR2PER.K/NEISER)+(LS2PER.K/NEILS))+(TOTEXP$.K)

$ Output to final demand or export

A GRGDP.K=(GDP.K-XGDP.K)/XGDP.K

5 Allocating capital for investment.

Set GRs - Calc Capital to be imported and required labour productivity improvements

A TGCF.K=IN2GCF.K+SR2GCF.K+LS2GCF.K+TR2GCF.K

Gross fixed capital formation from other sectors

A FTGCF.K=FIN2GCF.K+FSR2GCF.K+FLS2GCF.K+FTR2GCF.K Gross fixed capital formation from other sectors

A CAPINV.K=TGCF.K+IM2CF.K+IN2PER.K

Capital available for investment or consumption

A FCAPINV.K=FTGCF.K+FIM2CF.K+FIN2PER.K

A TRCF$.K=TRCF.K/NEIIND

A TGCF$.K=TGCF.K/NEIIND

6 Growth algorithm

In this growth algorithm any shortage in Capital (TRCF - total rate of capital formation) is supplied by importing capital. To prevent debt from increasing too fast the rate of exports from different sectors may be increased.

A CONS.K=IN2PER.K	Consumption (GJ82)
A FCONS.K=FIN2PER.K	Consumption (GJ)
A IM2CF.K=TRCF.K-TGCF.K	Imported capital (GJ82)
A FIM2CF.K=IM2CF.K	Imported capital (GJ)
A GRIN2X.K=GRIND.K	Growth rate of industry to capital formation

This can be set to grow faster if one wishes to supply capital internally rather than import it.

Critical growth rates.

A GRPER.K=0.016 Growth rate to final demand

The growth rate to final demand can be a function of the grwoth rate of population

N NGR=0.016 Initial growth rate

A GREXP.K=0.027 Growth rate to exports

A GENRCLP.K=0.013 General rate of change of labour productivity

7 Exports

Exports are calcuated in terms of $, GJ82 and embodied energy.

A TOTEXP$.K=(LS2EXP.K/NEILS)+(SR2EXP.K/NEISER)+(IN2EXP.K/
NEIIND)+^ (TR2EXP.K/NEITRA)+(TF2EXP.K/NEITF) Total exports ($)

A TOTEXPS.K=LS2EXP.K+SR2EXP.K+IN2EXP.K+TR2EXP.K+TF2EXP.K
Total exports (GJ82)

A FTOTEXP.K=FLS2EXP.K+FSR2EXP.K+FIN2EXP.K+FTR2EXP.K+FTF2EXP.K
Total exports (GJ)

8 Imports

A TOTIMP$.K=TOTIMPS.K/EIIMP Total imports ($)

A TOTIMPS.K=IM2PER.K+IM2IND.K+IM2TRA.K+IM2SER.K+IM2LS.K+
IM2TF.K+ IM2EL.K+IM2CF.K Total imports (GJ82)

A FTOTIMP.K=FIM2PER.K+FIM2IND.K+FIM2TRA.K+FIM2SER.K+FIM2LS.K
+FIM2TF.K+FIM2EL.K+FIM2CF.K Total imports (GJ)

N NIM2PER=2.3e9	Imports to consumption ($)
N NIM2IND=3e9	Imports to industry ($)
N NIM2TRA=3.43e8	Imports to transport ($)
N NIM2SER=8.3e8	Imports to services ($)
N NIM2LS=3.49138288e8	Imports to life support ($)
N NIM2TF=8.39509212e8	Imports to thermal fuels ($)
N NIM2EL=2540418	Imports to electricity ($)
N NIM2CF=1.1e9	Imports to capital formation ($)
N EIIMP=10E-3	Energy intensity of imports (GJ/$)

A GRIM2PR.K=GRPER.K Growth rate of imports to final demand

A GRIM2IN.K=GRIND.K Growth rate of imports to industry

A GRIM2TR.K=GRTRA.K Growth rate of imports to transport

A GRIM2SR.K=GRSER.K Growth rate of imports to services

A GRIM2LS.K=GRLS.K Growth rate of imports to life support

A GRIM2EL.K=GREL.K Growth rate of imports to electricity

A GRIM2CF.K=GRIND.K Growth rate of imports to capital formation

A TRDBAL.K=TOTEXPS.K-TOTIMPS.K Trade balance GJ

A TRDBAL$.K=TOTEXP$.K-TOTIMP$.K Trade balance dollars

9 International borrowing

L DEBT.K=DEBT.J+DT*(BOR.JK-REPAY.JK) International debt ($)

N DEBT=17E9 Initial debt ($)

R BOR.KL=BORROW.K Borrowing rate ($/yr)

R REPAY.KL=DEBT.K/PERIOD Loan repayments ($/yr)

C PERIOD=15 Lifetime loans (yr)

A BORROW.K=-NCASHFL.K International borrowing ($/yr)

R INT.KL=DEBT.K*INTRATE Interest paid ($/yr)

C INTRATE=.05 5% Real interest rate

A NCASHFL.K=TRDBAL$.K-INT.KL-REPAY.KL-INTAID.K

National cash flow

A INTAID.K=0 International aid $/yr

10 Energy efficiency and capital requirements

Total efficiencies for BAU scenario

A EFFINSR.K=0.99**(TIME.K-INTIME) efficiency for industry and services

N INTIME=TIME

Note this is a 1% increse in efficiency per year

A EFFOTH.K=0.995**(TIME.K-INTIME) efficiency for other sectors

Note this is a 0.5% increse in efficiency per year

* Thermal efficiencies

A GENTEFF.K=EFFOTH.K	General thermal fuel efficiency factor
A GENCPTH.K=GENCPF.K	General capital requirement to achieve energy efficiency

* Electric efficiencies

A GENEEFF.K=EFFOTH.K General electricity efficiency factor

A GENCPEL.K=GENCPF.K

A GENCPF.K=0

11 Energy balances

This energy balance checks the consistancy of of the energy analysis

A PRIMES.K=FOSTF.K	Primary fossil energy supply
A FENIN.K=PRIMES.K+FTOTIMP.K	Energy in (GJ)
A FENOUT.K=FCONS.K+FSR2PER.K+FDOMOUT.K+FTR2PER.K^	
+FLS2PER.K+FTOTEXP.K+FIM2PER.K	Energy out (GJ)
A FCHCPST.K=FTRCF.K-FTRDC.K	Change in capital stock (GJ)
A FNENIN.K=FENIN.K-FCHCPST.K	Net energy in (GJ)

FNENIN should equal FENOUT if the energy balances are correct.

Notes

1. For a full description of the macro function see Pugh (19xx).

Appendix 6: Description of the models included in the disk

The models included in the disk accompanying this thesis are briefly explained. The sections in the text that refer to the models is also included. The models are from Vensim (1988) or Professional Dynamo (Pugh, 1991).

1 Models from Chapter 13

Vensim models

CHAP147.VMF	Double set of accounts (section 2.5)
CHAP148.VMF	Slesser's method (section 2.6)

2 Models from Chapter 14

Vensim models

GLOBEA.VMF (Section 2)

GLOBEB.VMF (Section 2)

GLOBEC.VMF (Section 2)

GLOBED.VMF (Section 3)

GLOBEE.VMF (Section 3)

GLOBEF.VMF (Section 4)

3 Models from Chapter 15 and 16

Dynamo models used for the simulation of the scenarios in Chapter 16.

NZBASE.DYN	Base scenario for New Zealand (section 2.1)
NZGR1.DYN	1% growth rate (section 2.2)
NZGR2.DYN	2.5% growth rate (section 2.2)

NZGR3.DYN	3.5% growth rate (section 2.2)
NZSTRUCT.DYN	Structural change - high growth in services (section 2.3)
NZEFCP.DYN	Efficiency with capital requirements (section 2.4)
NZEFF1.DYN	High efficiency scenario (section 2.4)
NZEFF2.DYN	No efficiency (section 2.4)
NZREN.DYN	Renewable energy scenario (section 2.5)

4 Other models included on the disk

The following DYNAMO models further explain the double set of accounts.

GRNCOR.DYN
GRNCOR1.DYN
GRNCOR2.DYN
GRNCOR1.DRS
GRNCOR2.DRS

A word perfect document <double.doc> explains this series of models.

Appendix 7: Abstracts of papers presented during the course of this thesis

IPENZ Conference, Hamilton, 5-9th February 1993.
Chemical Engineering Technical Group.

SYSTEMS DYNAMIC SIMULATION OF DEVELOPMENT OPTIONS FOR NEW ZEALAND

Grant Ryan and John Peet

Key words: Sustainable development, Limits, Embodied energy, Dynamic simulation.

ABSTRACT

Starting from the position that "If a process is not physically possible, then it cannot be economically possible" (Slesser, 1982) we argue that whether a country's development process is likely to be sustainable is primarily a physical question, to be answered using the tools of physics, based on thermodynamics. In this paper, we describe how we are examining some dynamic aspects of the sustainability of New Zealand's development options.

Third Biennial Meeting
The International Society for Ecological Economics
"Down to Earth: Practical Applications of Ecological Economics"
October 24-28, 1994
San José, Costa Rica

ENERGY AS A MEASURE OF RESOURCE COST IN SYSTEM DYNAMICS MODELLING OF SUSTAINABILITY

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ABSTRACT

We describe the principles behind a system dynamics simulation model we are constructing of the New Zealand economy. The approach is based upon Slesser's ECCO methodology, in which stocks and flows of embodied energy are used to follow activity in the physical economy. By this means, a range of different indices of sustainability may be determined and assessed.

Structural information and initial conditions (stocks and flows) for the dynamic model were largely obtained from an energy-modified input-output transactions matrix and from data on capital stocks in the economy.

Following Slesser, we use the IFIAS convention, in which only nonrenewable (fossil or fissile) fuels are counted directly. The use of embodied energy as the numeraire raises some practical problems. Values obtained for outputs ("activities") are significantly affected if either the primary energy sources shift from nonrenewable to renewable sources or there are improvements in the productivity of energy use (energy conservation/efficiency). We address this issue in our algorithms, by including additional "accounts" (somewhat analogous to the economist's correction of nominal values to inflation-adjusted "real" values), to ensure that consistent and reasonable results for economic "activity" are obtained.

Paper presented to the Second International Symposium on Energy Based Models.
Institute for Ecology and Resource Management,
Edinburgh University
Scotland.
28-30 June, 1995

Methodological issues relating to embodied energy and growth in ECCO

Grant Ryan and John Peet

Abstract

This paper investigates a number of methodological questions about ECCO models. The two main issues discussed are:

- the growth algorithm in ECCO models.
- the use of embodied energy as a numeraire and

A significant problem with ECCO is the growth algorithm, specifically the method of allocating

industrial output between investment and consumption. If the fraction of industrial output not consumed is high, then industrial output will grow at a high rate; if the fraction not consumed is low, industrial output may fall. It is not clear what determines this "fraction not consumed", or fraction invested, in ECCO models. The choice of the fraction invested implies a certain rate of technological progress, and this rate of technological improvement may in fact be the critical limit to growth. The model can be modified to make these issues explicit. The growth algorithm is also modified to allow for changes in the productivity of capital.

The second significant problem with ECCO is related to the use of embodied energy as a numeraire. The embodied energy of goods and services does not necessarily directly correlate with the volume of economic output, as the quantity of embodied energy required to produce economic output changes over time. This means that embodied energy is not a reliable measure of economic activity. We know that prices do not measure economic output accurately, and must be converted into "constant dollars" to give a dimensionless index of the volume of economic production. Similarly, embodied energy can be converted into "constant embodied energy" to give a dimensionless index of the volume of production. In this way both economic activity and the embodied energy required to produce economic output can be measured, without assuming they are the same thing.

Both of the recommended changes cause a significant change in the behaviour of ECCO models and the type of information that can be found from them. In the following discussion it is assumed that the reader is familiar with the basic concepts of the ECCO methodology.

Inaugural Conference
Australia and New Zealand Societ for Ecological Economics
Opal Cove Resort
Coffs Harbour NSW
Australia
November 19 to 23, 1995

Embodied energy in systems dynamic simulation modelling of economic growth.

Grant Ryan and John Peet

Abstract

In the development of ecological economics, the distinction has been made between issues of allocation, distribution and physical scale (Daly, 1991). This paper addresses the third issue, of clarifying the nature and extent of limits to physical growth of an economy.

The approach we use (based on Slesser's ECCO methodology) uses embodied fossil energy as a measure of the depletable natural capital used in economic activity (in our case, specifically for the New Zealand economy). Our model structures reflect economic data obtained from energy-modified input-output surveys, and are fully dynamic, incorporating feedbacks and nonlinearities.

Our aim is development of an understanding of some of the critical flows from nonrenewable physical resources associated with economic growth under different scenarios. The purpose of our approach is therefore quite different from conventional economic growth models, which generally focus on prediction of short-to-medium term economic growth rates, using some form of utility maximisation as the driver. In our

models the focus is simulation of either (a) the growth possibilities from different scenario assumptions about resource flows and available technologies or (b) the resource flows and technologies required for a specific growth rate. It is our belief that understanding of critical long-term physical limits to economic growth can be enhanced by analysing energy requirements, with reference to the laws of thermodynamics.